PRIORITIZING WATER PIPE REPLACEMENT AND REHABILITATION BY EVALUATING FAILURE RISK

A Thesis

by

SANG HYUN LEE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2011

Major Subject: Biological and Agricultural Engineering

Prioritizing Water Pipe Replacement and Rehabilitation

by Evaluating Failure Risk

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Approved by:

Chair of Committee,	Vijay P. Singh
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ABSTRACT

Prioritizing Water Pipe Replacement and Rehabilitation

by Evaluating Failure Risk.

(December 2011)

Sang Hyun Lee, B.S., Kyung Hee University

Chair of Advisory Committee: Dr. Vijay P. Singh

Essential to human life is water. Drinking water, in particular, is of utmost significance for all living creatures including man. An examination of the transmission process of drinking water reveals the great importance of pipe lines. Water pipe lines delivering water today may encounter serious problems. Corrosion has caused deterioration in some pipe lines, which contributes rust to drinking water, a serious water quality problem. In addition, pipe line failures have caused social issues, such as suspension of the water supply. This study developed a model to estimate the life expectancy and residual life of a pipe based on the assessment of failure risk in order to evaluate the current failure possibility and predict when the pipe will reach the point of failure. The developed model was used to assess the failure risk of water pipes based on the general data and pipe sources of the Changwon, South Korea, water pipes. The efforts to diagnose and evaluate water pipes are limited to the assessment of current pipe conditions, which is why they can easily determine the priority of rehabilitation based on the current pipe conditions, but have a hard time getting information about how the pipes have deteriorated to the point of requiring rehabilitation. The objectives of this study are to: (1) develop a model for estimating corrosion rates and residual thickness of water pipes, (2) assess loads and stress affecting water pipes, (3) estimate damage risk, and (4) calculate safety factors. According to results of this study, most of the ductile cast iron pipes with no lining need to be replaced. On the other hand, ductile cast iron pipes with cement mortar lining and steel pipes were in good condition. Results of the study could help reduce rehabilitation costs and secure water quality after renovation. Thus it would contribute to the safe and stable operation and management of pipe networks by increasing the life of water pipes.

To My Wife, Kyungjin Hwang

It is hard to find any words that

express all my gratitude and my love,

for your belief in me, your unconditional support,

patience, love, advice, and willingness to help in any possible way.

Thank you so much, I love you

ACKNOWLEDGMENTS

Special thanks to Dr. V. P. Singh for his guidance and advice in this research and also for giving me an opportunity to participate in this project. I could not have accomplished all this without Dr. Singh's assistance. My appreciation goes to my committee members, Dr. P. Smith and Dr. R. Wurbs, for their guidance and support throughout the course of this research.

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1. INTRODUCTION

1.1 Problem Statement

Damage to water pipes is influenced by various factors, including design, construction, and management. Grey cast iron pipes without any coating or lining in or outside and unlined ductile iron pipes (DIPs) are under the direct influence of corrosion after their layout. Cement mortar-lined ductile cast iron pipes or steel pipes face problems after carbonation or exfoliation of coating material. Corrosion products, such as nodules inside pipes, reduce the cross-sectional flow area, make it difficult to secure the required water volume and pressure, and cause various water quality problems, including red water, thus ultimately robbing water pipes of their original functions.

Structurally speaking, corrosion, in and outside, decreases pipe thickness and strength and reduces pipe resistance against internal and external loads, causing structural damage to water pipes [1]. In general, pipes after their layout get smaller in thickness with time due to corrosion, drop in innate strength, and eventually suffer physical failure. Potential failure risk can be assessed by comparing the load affecting the residual strength of the pipe with stress on the pipe matrix caused by the load.

The technologies of diagnosing and assessing water pipes have evolved around the deterioration point assignment method, which assigns deterioration points to the concerned pipe according to the importance of pipe damage-related indirect factors,

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This thesis follows the style of Corrosion Science.

namely years of burial, type of pipe, pipe diameter, type of soil, location of burial, water pressure, and history of damage, and marking the deterioration grade based on the results of comprehensive evaluation. While the deterioration point assignment method is easy to apply, it lacks the attention to correlation between the pipe condition and the deterioration point and objective criteria for judgment. It has also been considered difficult to set up renovation plans based on the prediction of renovation time according to the pipe condition and determining the accurate scope of renovation section [2].

In addition to the deterioration point assignment method, many different techniques are being developed these days to raise the credibility of factors used in the estimation of deterioration. In particular, active research efforts have been invested into the break-even analysis approach, which estimates an economical replacement time at the break-even point by analyzing the repair costs based on the long damage history (damage rate), and a mechanistic or physical model which estimates the damage risk of deteriorated water pipes by evaluating their physical deterioration and provides data for short- and long-term renovation plans [2,3 and 4].

Studies have been focused on unlined grey cast iron pipe in most cases in North America, including the U. S. In Korea, however, where cement mortar lining cast iron pipes and steel pipes as well as unlined grey cast iron pipes and unlined ductile cast iron pipes are high in percentage and have been buried for many years (over 26 years for cement mortar lining ductile cast iron pipes and over 30 years for steel pipes), it is urgent to develop a model for deterioration estimation for those types of pipe.

One can make rational renovation plans for water pipes by estimating the time of damage to the metal pipes buried underground or their life span and thus offer enormous assistance in terms of economy and stable water supply.

The main objective of the study was therefore to propose a model for estimation of residual thickness by evaluating the diminution of physical strength of pipe according to corrosion. The study ultimately set out to develop a model for evaluation of damage risk (structural safety) to estimate the time of damage or residual life by assessing the stress due to internal and external loads.

1.2 Research Objectives

The objectives of this study are: (1) develop a model for estimating corrosion rates and residual thickness of water pipes, (2) assess loads and stress affecting water pipes, (3) to estimate damage risk, and (4) calculate safety factors. Results of the study could help reduce rehabilitation costs and secure water quality after renovation. Thus, it would contribute to the safe and stable operation and management of pipe networks by increasing the life of water pipes.

1.3 Research Scope

In order to accomplish the study objectives, this study requires information on the following aspects of pipe deterioration.: (1) estimation of pipe corrosion rate and depth; (2) estimation of the residual strength; (3) calculation of maximum loads to which water mains are exposed; and (4) calculation of a Safety Factor (SF) for each pipe as the residual strength of the pipe divided by the pipe stresses resulting from the maximum loads to which the pipe is subjected. The study utilizes data on pipe line facilities managed by the Korea Water Resources Corporation (K-Water).

2. LITERATURE REVIEW

This section examines methods to calculate pit depth and residual strength resulting from pipe corrosion, one of the major causes of deterioration in water pipes.

2.1 Pipe Failure

For model development, determination of factors causing pipe failures is important. The main factors are listed in Table 2.1.

Table 2.1 Factors causing pipe failures [2]

Factors	Examples
Pipe characteristics	Diameter, wall thickness
Structural properties	Bursting tensile strength, modulus rupture
Longitudinal and transverse forces and stress	Bending stress, thermal contraction stress
External loads	Earth load, frost load
Aging	Pipe manufacturing techniques, strength of main
Corrosion	Internal corrosion, external galvanic corrosion
Soil characteristics	Soil moisture, soil resistivity

In a study on pipe failures Kane [5] concluded that:

1. The break rate among clean and lined cast iron pipes is about a quarter

of the break rate of unlined cast iron pipes. Thus, cleaning and lining are recommended for structural soundness of unlined cast iron pipes.

2. Break rates in corrosive soils are double the rates of pipes in non-corrosive soils.
3. Break rate is 50% higher in soils that expand and contact due to soil moisture.
4. Cold weather affects break rates both by the duration and the severity of cold weather.
5. The highest number of breaks occurs in winter months.

2.2 Methods to Assess Failure Risk of Water Pipes

Approaches to the determination of renovation priorities of water pipes are categorized into (1) the deterioration point assignment (DPA) method, (2)) break-even analysis, (3) failure probability and regression methods, and (4) mechanistic models [2].

2.2.1 Deterioration Point Assignment (DPA) Method

This method provides a scoring system for pipes given a set of factors depending on various characteristics and the surrounding environment of pipes, such as pipe material and size, type of soil, and water pressure. The numerical values for these factors are assigned into several class intervals of failure score. A total failure score for any pipe is the value of the summation of the class interval failure scores.

Thus, when the total failure score exceeds a threshold value, the pipe should be replaced or rehabilitated.

2.2.2 Break-even Analysis

Break-even analysis is based on repair cost and replacement cost simultaneously. A predictive technique for pipe breaks is important to estimate the replacement cost with the predicted break occurrence time. The present value cost of replacing a pipe decreases over time, and the present value of cumulative repair costs increase over that same time period. Thus, the total cost is the sum of present values of replacement and cumulative repair. Break-even analysis estimates the optimum economic time to replace the pipe with the total present worth the cost.

2.2.3 Failure Probability and Regression Method

The method is useful to estimate the probability of future failure which is related to the DPA method. Both the failure probability and DPA method use the same deterioration factors, with a predictive capability by assessing the probability of a pipe's survival. For example, Clark et al. [6] proposed certain multiple regression equations for the number of years from installation to the first repair. Another equation was also proposed for the number of repairs over a time period measured from the time of the first break. These equations had coefficients of determination (R^2) of 0.23 and 0.47, respectively. Thus, while Clark et al. [6]'s procedure was a significant improvement in predicting pipe breaks, it did raise some concerns because of the low values of the coefficients of determination.

2.2.4 Mechanistic Model

Mechanistic models simulate both the deterioration of a pipe over time and the load. This method relies on detailed pipe and environmental data. Stacha [7] proposed a method of determining the time of replacement by comparing annual repair costs with annual replacement costs, raising the need to consider other factors, such as water quality and transportation capacity in such a case.

Male et al. [8] reported that the discount rate affected the selection process of alternatives such as replacement and repair. Kleiner et al. [9] took into account repair costs based on the increased transportation capacity due to lining, and found that the decreased C value increased water heads and reduced pressure, and obtained optimal replacement time by putting together changing mass, energy balance and water heads. Grablutz and Hanneken [10] proposed an economic model that added repair costs, which compared accumulated repair costs in the future, to the replacement costs and converted them into total current value costs, suggesting that the most economical time for pipe replacement is when total costs are the lowest and that non-economy items should also be considered when making the final replacement decision.

Su et al. [11] and Wagner et al. [12] showed an alternative format of credibility restriction factors based on the probability to meet demand and pressure requirements on the nodes in the damage structures of diverse pipe networks. Goulter and Kazemi [13] discovered spatial and temporary pipe damage clustering in Winnipeg City and proposed the NPDM (Non-homogeneous Poisson Distribution Model) to estimate the probability of successive damage after the first damage incident on water pipes.

Mavin [14] pointed out the need to carefully select data when developing a damage model and chose not to consider damage that happens three years after burial or within six months from the previous damage incident, believing that such damage types have nothing to do with construction defects or structural damage to the pipe.

Shamir and Howard [15] conducted regression analysis of the history of pipe damage to develop an exponential function to estimate the number of pipe damage and determined optimal time for pipe replacement by comparing the pipe repair costs with the pipe replacement costs.

Walski and Pellicia [16] proposed a model based on the history of pipe damage to reflect the pipe damage rate. Their model shared some similarities with that of Shamir and Howard [15] with some revisions. Walski and Pellicia [16] suggested a calibration coefficient to reflect the influence of temperature on pipe damage and also warned that the use of temperature calibration coefficient might make a bigger estimation of future damage rate since it was difficult to estimate coldness in winter.

Mavin [14] developed a regression model using correlations between years of burial and intervals between repairs based on the selected data. Karaa et al. [17] proposed a procedure to determine the replacement time of a pipe whose damage had been demonstrated. In the procedure, they divided the pipes into so-called "bundles" based on renovation, replacement and similarities of the pipes to be constructed according to the damage model.

Rossum [18] proposed a model that considered changes to the depth of pitting corrosion according to time, soil environment, and years of burial. There were also many other models proposed on load and stress, and they covered stress created by temperature changes (Wedge, [19]; Habibian, [20]) or freezing load (Cohen and Fielding, [21]; Fielding and Cohen, [22]; Rajani and Zahn, [23]).

Philadelphia Water Department (PWD) [24] reported diverse ways of structural damage on water pipes.

Rossum [18], Kumar et al. [25] and Ahammed and Melchers [26] proposed a model of corrosion rate.

Roy F. Weston Inc. and TerraStat Consulting Group [27] developed the Pipe Evaluation System (PIPES) model for use by the Seattle Public Utilities to evaluate the rehabilitation needs of pipes in the system. The PIPES model consisted of three sub models: deterioration, vulnerability, and criticality.

Duan et al. [28] took into account the optimization and reliability of pumping system in the pipe network, which topic was also covered by Lansey and Mays [29] and Park and Liebman [30]. Loganathan et al. [31] and Sherali et al. [32] investigated into methods related to the optimization of pipe networks. Table 2.2 shows that summary of previous research studies.

Table 2.2 Summary of previous research studies [33]

Author(yr.)	Problem	Objective	Mathematical tool
Woodbum (86) Lansay (92) Kim (94)	Hydraulic deficiency	Minimize cost due to increase pumping	Mixed integer non-linear programming
Li (92)	Structural deficiency	Minimize costs for each pipe based on rehabilitation	Semi-Markov model; Probabilities calculated with hazard and survival functions. Optimization achieved with non-linear programming.
Cabrera (94)	Leaks	Determine best time to start leak detection program	Expert system. Pragmatic methodology.
Halla (97)	Structural deficiency(breaks) and hydraulic deficiency	Minimizes costs+maximize benefits+respect a given budget	Structured Messy Genetic Algorithm
Deb (98)	Structural deficiency	Determine length of water main to rehabilitate each year	Survival functions with limited data(realistic approach)
Kleiner(98)	Hydraulic deficiency	Minimizes costs	Dynamic programming
Loganathan (02)	Structural degradation	Predict break rate of a system	NHPP-determination of a threshold break rate based on economic considerations
Shamir and Howard (79)	Structural degradation(breaks)	Model number of breaks with time	Regression
Clark (82)	Structural degradation(breaks)	Model number of breaks based on risk factor	Regression
`O'day (89)	Structural degradation(breaks)	Model age at 1st break based on risk factor	Regression

Table 2.2 Continued

Author(yr.)	Problem	Objective	Mathematical tool
Andreau (86, 86a) and marks (88)	Structural degradation(breaks)	Identity relevant risk factor	Survival analysis(PHM)
Eisenbers (94, 99) and le Gatt (00)	Structural degradation(breaks)	Prioritize "at risk"pipes. Obtain probability of failures	Survival analysis(WPHM-Monte Carlo simulation to forecast future number of breaks)
Elbanousy (97)	Structural degradation(breaks)	Optimization, minimizes costs	WPHM to calculate failure probabilities-life cycle cost assessment/cost functions
Rostum (00)	Structural degradation(breaks)	Prioritize "at risk"pipes.	Survival analysis (NHPP-WPHM)
Malandain (00)	Structural degradation(breaks)	Prioritize "at risk"pipes.	Poisson regression model-WPHM+Exponential model
Utilnets (99)	Corrosion+external loading	Calculate remaining service life of each pipe	Deterministic model(CIP)
Rajani (00)	External corrosion+external and internal loading	Failure of risk and predict remaining service life of each pipe	Deterministic model(CIP);external corrosion model+residual strength model
Deb (02)	External corrosion+external and internal loading	Failure of risk and predict remaining service life of each pipe	Mechanistic model(CIP);external corrosion model+residual strength model

2.3 Review of Studies on Corrosion and Residual Life of Pipes

2.3.1 Corrosion

Corrosion is a general term for the rusty state of metal, having originated in a Latin word, “rodere”(to gnaw). It refers to matter being groundor attacked by a chemical or electrochemical reaction. Metal is produced by refining and transforming ore. The process involves a massive amount of energy in the form of heat, which means metal is usually used with high energy content inside. Once being exposed to oxygen or moisture under the ground or in the atmosphere, metal emits its stored energy and starts the corrosion process. It is metal returning to its original state. Corrosion proceeds rapidly with high energy content, but the rate slows down greatly if metal is used in the form of ore. Metal corrosion is the phenomenon of metal being deteriorated by its surrounding environment and electrochemical or chemical reaction. The most important characteristics of corrosion thus occur by an electrochemical process. Generally speaking, the metal surface in a solution is a venue for the activities of countless local batteries with local anodes (low electrical potential) and cathodes (high electrical potential) of micro areas according to the underwater environmental conditions, as shown in Figure 2.1.

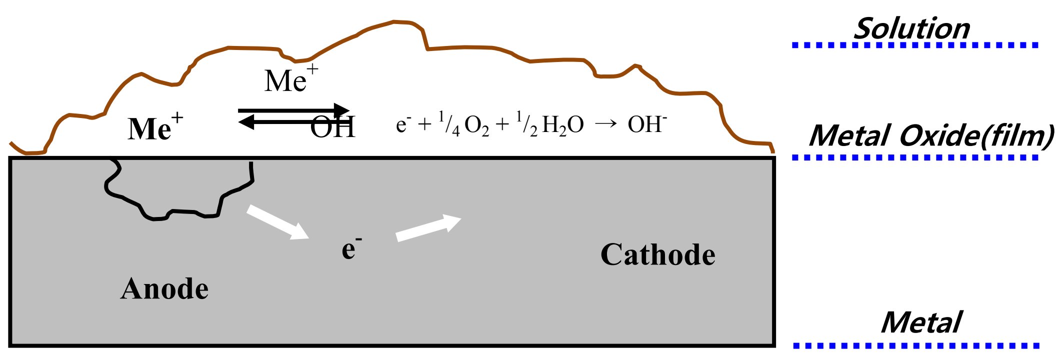


Figure 2.1 Localized corrosion of metal surface

As shown in Figure 2.2, water pipes buried underground develop rust or scale caused by corrosion in the internal and external upper sections. The pipes themselves form a Graphitic Corrosion Product (GCP), which disguises corroded pipes. Since it has no structural hardness, one should measure maximum internal and external corrosion depth after eliminating the scale [34].

Figure 2.2 Rust or scale is formed in the internal and external upper sections by corrosion

Rossum [18] developed a model to predict a pit outside the pipe according to soil characteristics. The Rossum Model is a representative corrosion rate model based on soil corrosion properties. It has been also developed and empirical models have been reported based on the extensive collection of data. The latest one is a two-phase model developed by Rajani et al. [4] which represents two phases of corrosion rate. They reported that corrosion proceeded fast (exponential pit growth) in the first phase and then slowed down and showed a slow linear growth in the second phase. With the passage of time, corrosion first proceeds fast and then is gradually deterred by corrosion products (FeO) (Ahammed and Melchers, [26]), which was considered by Rajani et al. [4].

Secondary contamination by the internal corrosion of water pipes is a serious problem. There have been ongoing investigations on how to set a corrosion index and control corrosion in order to address the problem. The representative internal corrosion indexes concerning water quality corrosion properties are the Langelier Saturation Index (LSI) (Langelier, [35]) and Ryznar Saturation Index (RSI) (Ryznar, [36]). The internal corrosion of water pipes can be controlled as follows:

a) The corrosion properties affecting the pipes are lowered by changing water quality.

b) A protective wall or lining is inserted between water and pipe.

c) Corrosion is controlled by changing the types of pipe and system design.

2.3.2 Corrosion Rate

In North America, including the U.S., most of the pipes buried underground are unlined Cast Iron Pipes (CIPs). Since drinking water does not have any corrosion elements, such as chloride, they are not subject to corrosion. Most of the studies on pipes' corrosion have been concerned with external corrosion rather than internal corrosion.

Recognizing that the major cause of external corrosion is soil corrosion, soil properties, including soil resistivity, pH, soil sulphide and moisture and their relationships with the depth of external corrosion have been studied.

A decrease in the pipe thickness is attributed to corrosion and can happen globally or locally. However, researchers have assumed the reduction rate of pipe thickness or corrosion rate as a simple constant and used it as such, thus causing much controversy (Ahammed and Melchers [26]; Romanoff, [37]).

Recently Rajani et al. [4] presented a two-phase model, which divides corrosion rate into two phases. In the first phase, corrosion proceeds fast (exponential pit growth), whereas in the second phase, it slows down with a slow linear growth. This model structure considers the fact that corrosion proceeds faster in the early days and then is gradually deterred by corrosion products.

Table 2.3 Most commonly used models for surface corrosion

Model	Reference	Parameters
$d = k\,T^n$ (Power model)	Kucera and Mattsson (1987)	d = Depth of corrosion pit (mm) k = Constant (≈2) n = Constant (≈0.3) T = Exposure time (yr.) d_T = Corrosion rate (mm/yr.)
$d = K_n Z^n$ (Rossum model)	Rossum (1969)	K_n = Constant ρ_{soil} = Soil resistivity pH = Soil acidic or alkaline nature n = Related to soil redox potential
$d = aT+b(1-e^{-cT})$ $d_T = a + bce^{-cT}$ (Tw□-phase model)	Rajani et al. (2000)	a = Final pitting rate constant (typical value; 0.009 mm/yr b = Pitting depth scaling constant (typical value; 6.27 mm) c = Corrosion rate inhibition factor (typical value; 0.14 yr.$^{-1}$)
$d_t = \frac{d(T) - dT(T_o)}{(T - T_o)}$ (Linear model)	Sheikh et al. (1990)	d(T) = Pit depth at time T $d(T_o)$ = Pit depth at time T_o

The models for corrosion rate, shown table 2.3, encompass a power model, the Rossum model, the Rajani model and a linear model.

According to Doyle [38], the relationship between soil resistivity and depth of external corrosion is exponentially in inverse proportion, as shown in Figure 2.3. The external pitting rate of a cast-iron water main decreases as soil resistivity increases.

On the other hand, Doyle [38] showed that the relationships of soil sulphide, pH, and age of pipe are not related to the maximum external pitting rate, as shown in Figures 2.4 – 2.6.

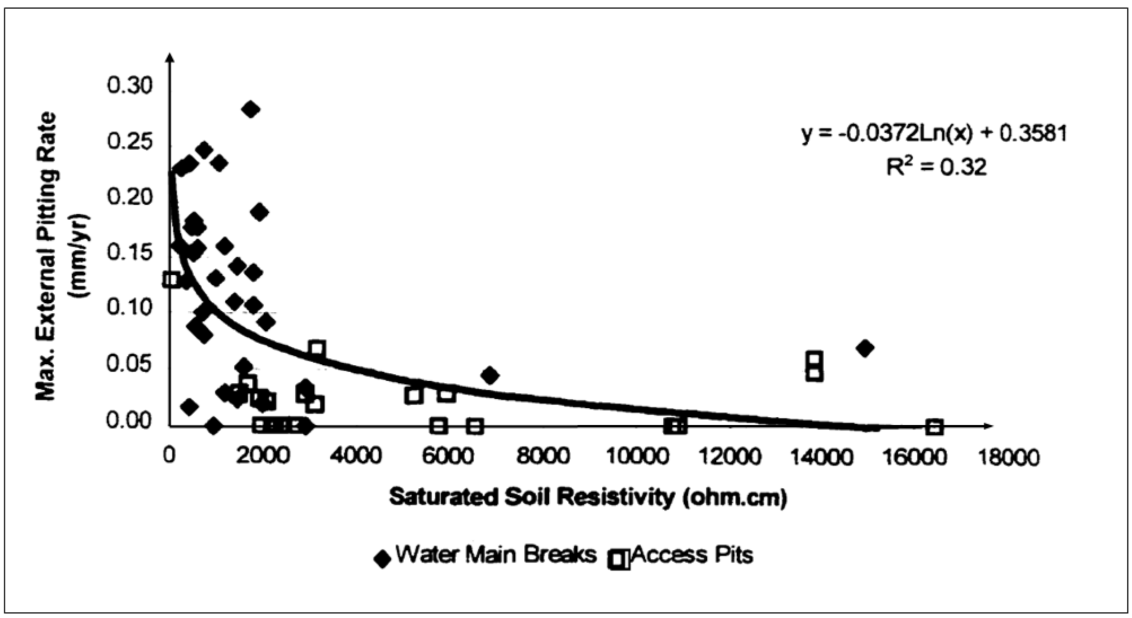


Figure 2.3 Maximum external pitting rate vs. soil resistivity [38]

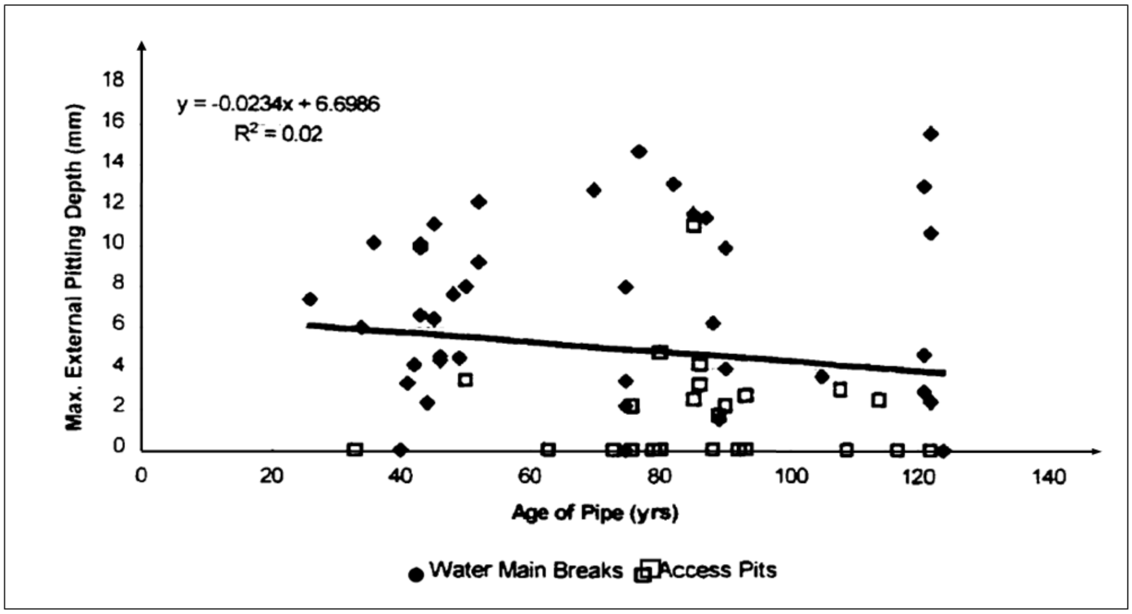


Figure 2.4 Maximum external pitting depth vs. age of pipes [38]

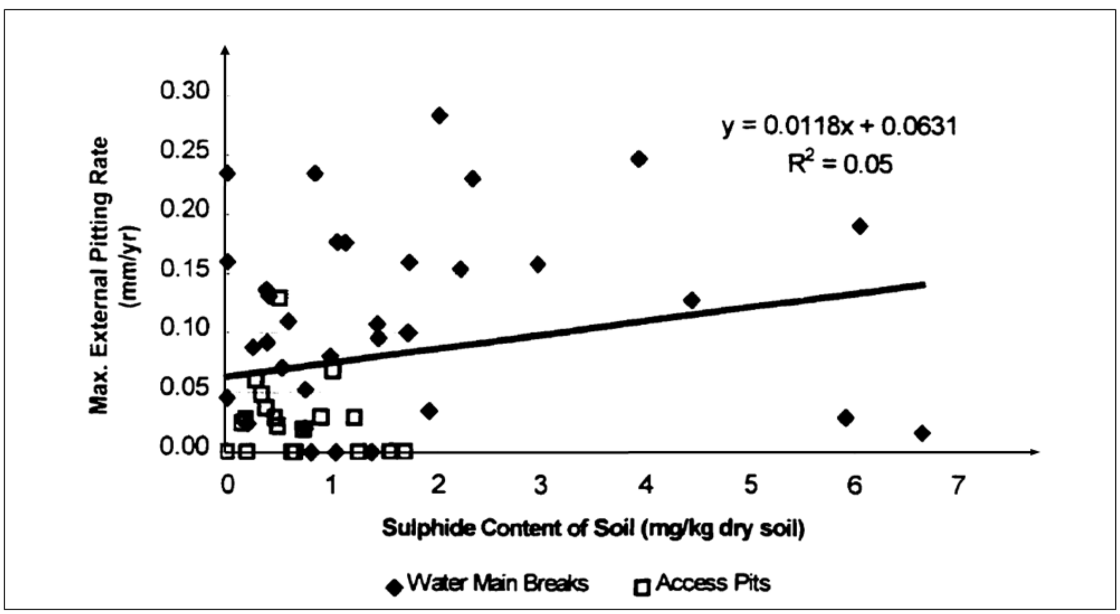


Figure 2.5 Maximum external pitting rate vs. soil pH [38]

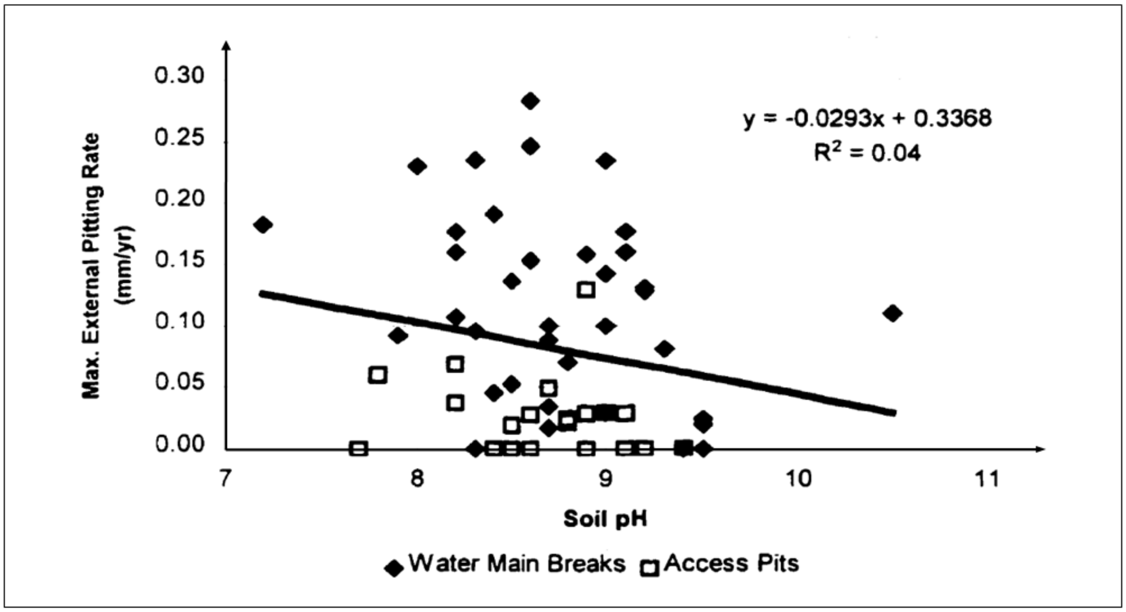


Figure 2.6 Maximum external pitting rate vs. sulphide content of soil [38]

In addition, Rajani et al. [4] mention that Rossum's model based on electrochemistry and soil properties is a corrosion model to predict corrosion pit depth and rates. However, it is limited to estimating the remaining service life of grey cast iron mains. The developed exponential model provides better estimates of the remaining service life, although the surrounding soil conditions are ignored for determining the corrosion pit depth and rate of the mains.

2.3.3 Residual Life of Pipes

In Deb et al. [2], the residual life of a pipe is the crucial factor in determining water main renewal priorities. Figures 2.7 and 2.8 show that external loads, internal loads, and temperature changes create various components of stress on the pipe wall, including ring stress, hoop stress, longitudinal stress, and flexural (bending) stress;

therefore, pipes are manufactured to withstand certain loads described in terms of the longitudinal tensile strength, flexural strength to withstand bending as a beam, ring strength to withstand crushing load given by the modulus of rupture, and bursting strength to withstand radial pressure.

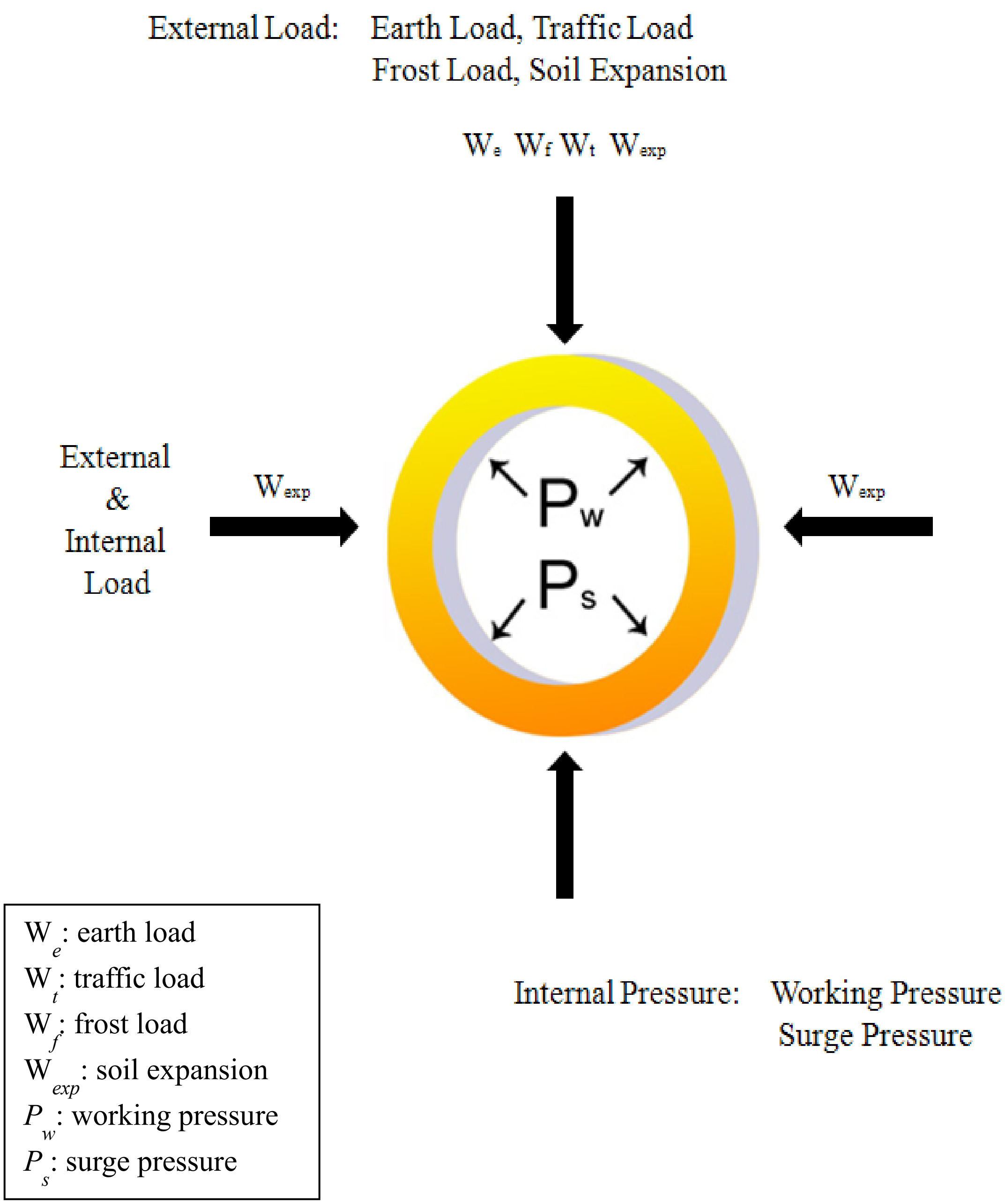


Figure 2.7 Internal and external load on water pipes [2]

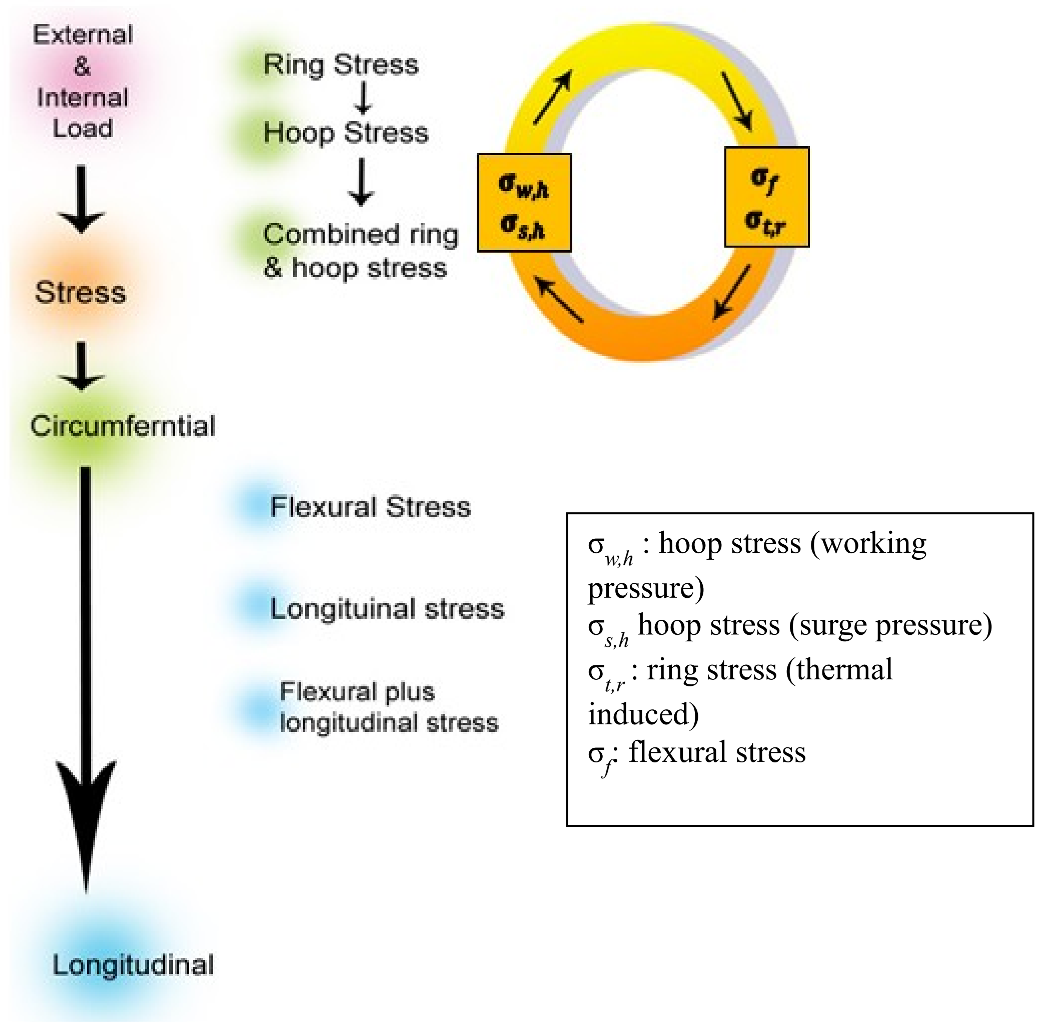


Figure 2.8 Stress on water pipes [2]

Ring stress represents the stress that is induced circumferentially in the pipe wall. Flexural stress represents a bending stress on a beam simply supported at the ends with the central span of the beam unsupported. Hoop stress is computed for two cases: working pressure with water hammer pressure. Combined ring and hoop stress represent the effect of both external loads and internal pressure. Longitudinal stress occurs due to internal pressure, sudden temperature change and effect of Poisson's ratio.

Typically, the ratio between the strength of the pipe and the stresses on a pipe is thought of as a margin of safety factor (SF). The pipe material and thickness are designed and selected to meet a certain SF. Once a pipe is put into use, it faces a deterioration process and continuously loses wall thickness. The SF of the pipe decreases as the residual strength of the pipe decreases along with pipe wall thickness. Theoretically, the SF of a pipe will be below 1.0 at the time of failure. Table 2.4 shows that safety factors (SF) of water pipes.

Table 2.4 Safety factors of water pipes (CIP) [2]

Safety factor	Variable
Safety factor for hoop stress $SF_h = \frac{\sigma_{bts(res)}}{\sigma_h}$	SF_h = Safety factor for hoop stress $\sigma_{bts(res)}$ = Residual bursting tensile strength, kg_f/cm^2 σ_h = Total circumferential stress, kg_f/cm^2
Safety factor for ring stress $SF_\theta = \frac{\sigma_{rmr(res)}}{\sigma_{\theta,total}}$	SF_θ = Safety factor for ring stress $\sigma_{rmr(res)}$ = Residual circumferential flexural bursting strength, kg_f/cm^2 $\sigma_{\theta,total}$ = Total circumferential flexural stress, kg_f/cm^2
Safety factor for circumferential stress by internal and external pressure $SF = \frac{-\left(\frac{P_t}{P_b}\right) + \sqrt{(\frac{P_t}{P_b})^2 + 4(\frac{W_t}{W_b})^2}}{2(\frac{W_t}{W_b})^2}$	SF= Safety factor for circumferential stress by internal and external pressure W_t = External load, kg_f/lin. cm W_b = Bursting load, kg_f/lin. cm P_t = Internal pressure, kg_f/cm^2 P_b = Bursting pressure, kg_f/cm^2

Table 2.4 Continued

Safety factor	Variable
Safety factor for longitudinal flexural stress $SF_f = \frac{\sigma_{mr(res)}}{\sigma_f}$	SF_f = Safety factor for longitudinal flexural stress $\sigma_{mr(res)}$ = Residual longitudinal flexural bursting strength, kg_f/cm^2 σ_f = Longitudinal flexural stress, kg_f/cm^2
Safety factor for longitudinal stress $SF_f = \frac{\sigma_{ts(res)}}{\sigma_{l,total}}$	SF_l = Safety factor for longitudinal stress $\sigma_{ts(res)}$ = Residual tensile strength, kg_f/cm^2 $\sigma_{l,total}$ = Total longitudinal stress, kg_f/cm^2
Safety factor for longitudinal and flexural stress $SF_{i,f} = \frac{\sigma_{ts(res)}}{\sigma_{l,f}}$	$SF_{l,f}$ = Safety factor for longitudinal and flexural stress $\sigma_{ts(res)}$ = Residual tensile strength, kg_f/cm^2 $\sigma_{l,f}$ = Longitudinal and flexural stress, kg_f/cm^2

3. FACTORS AFFECTING PIPE CORROSION

3.1 Corrosion of Water Pipes

3.1.1 Causes of Corrosion

There are two kinds of corrosion occurring in water pipes; one is internal corrosion, and the other is external corrosion. The former is usually influenced by water quality, while the latter is under the influence of soil humus although it depends on the external environments.

Water quality factors affecting internal corrosion are divided into three categories: physical, chemical, and biological. Physical factors include flow rate and temperature; chemical factors include dissolved oxygen (DO), pH, alkalinity, residual chlorine, and dissolved solids; and biological factors include bacterial and viral activities.

Of those factors, the physical and chemical ones as DO, pH, residual chlorine, alkalinity, dissolved solids, water temperature, and electric conduction have a direct influence on corrosion. These factors are interactive and cause corrosion; together they are more effective than individually.

3.1.2 Process of Corrosion

The process of corrosion is as follows:

(1) Fe dissolves or oxidizes upon contact with water and oxygen:

$$Fe \rightarrow Fe^{2+} + 2e^{-} \tag{3.1}$$

(2) Dissolved on the surface, Fe^{2+} reacts with water:

$$Fe^{2+} + OH^{-} \rightarrow Fe(OH)_2 + H_2O \rightarrow Fe(OH)_3 \tag{3.2}$$

(3) Formed on the surface is a corrosion nodule structure.

The anode of the local battery distillates corrosion current, and metal is eluted in an ion state. To explain with an example of iron, oxidation and reduction reaction take place at the anode and cathode, respectively, as in the following equation. The anode is the surface where current is distillated from metal into solution, and the cathode is the surface where current is flown into metal.

3.1.3 Growth of Corrosion

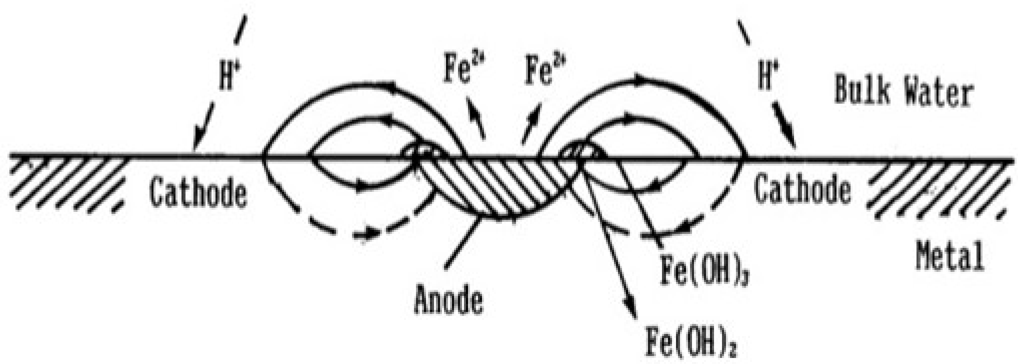


Figure 3.1 Localized corrosion of iron surface

$$\text{Anode}: \quad Fe \rightarrow Fe^{2+} + 2e^- \tag{3.3}$$

$$\text{Cathode}: \quad {}^{1}\!/_{2}O_2 + H_2O + 2e^- \rightarrow 2OH^- \tag{3.4}$$

$$ {}^{1}\!/_{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{3.5}$$

$$2H^+ + 2e^- \rightarrow H_2 \tag{3.6}$$

The electrochemical theory involved in corrosion has been confirmed by many different experimental studies. The theory dictates that there are sections with different electrical potential levels on the metal surface in the solution due to all kinds of reasons and that the many resulting local short-circuit electrical potentials cause corrosion on the metal surface of the anode. Figure 3.1 shows that localized corrosion of iron surface.

3.1.4 Types of Corrosion

There are many different types of corrosion according to the material, structure and scale of the pipe, formation of oxidation protective film, and hydrographical conditions. In addition, the forms of corrosion widely vary from uniform corrosion to localized corrosion. The most commonly used categorization is based on the appearance of corroded metal.

Uniform corrosion occurs uniformly on the whole metal surface but localized corrosion occurs on some part of metal.

Macroscopically localized corrosion starts with a structural defect and expands to the end of defect, thus it is distinguishable from microscopically local attack. There are several types of macroscopically localized corrosion, described below.

Galvanic corrosion occurs two metals are in contact with each other in a corrosive solution environment. The metal with high electrical potential becomes the cathode, and the metal with low electric potential becomes the anode and gets corroded. Corrosion occurs because the metal to become the anode sucks up electrons by coming in contact with the metal to become the cathode. Since the two metals are in contact with each other, electrons are exchanged between them. The enumeration of metals and alloys in the order of corrosion electrical potential is called the galvanic series.

Erosion corrosion occurs when the protective membrane formed by the abrasion force of water is broken and the metal gets exposed. It is observed at pipe laying, valves, pumps, tees, elbows where the velocity of moving fluid abruptly changes due to shock, turbulent flow, and velocity of the moving fluid.

Crevice Corrosion is a dense type of corrosion that occurs in the gap of the surface inside the pipe or within the protected area. It usually occurs in holes, on the gasket surface, pipe joints, surface deposition, and small-scale stagnation area formed by corrosion products.

Pitting is a non-uniform type of corrosion that is formed in a groove or hole on the surface of a water pipe and causes local damage. It starts at a part that is unstable on the surface, is scratched, or has a deposit and proceeds in intensity.

Exfoliation is a special type of intergranular corrosion, where exfoliation usually takes place in high-strength aluminum alloy. It can also be observed in an alloy that is formed through extrusion under a lot of pressure, or has a fine structure that tends easily to stretch.

Selective leakage is a type of corrosion in which zinc or lead is selectively eliminated from brass, lead from lead-tin solder, or calcium from the cement mortar lining of a steel pipe. It is caused by pH, alkalinity, solidity or silicon concentration, as well as a chemical used to eliminate calcium, manganese, and iron from the process of water treatment.

Microbiologically Influenced Corrosion (MIC) is caused by bacterial activity. There are anaerobic sulfate-reducing bacteria (SRB) and aerobic iron oxidation bacteria that cause corrosion. Corrosion cases by SRB have been collected from water pipes and urban gas pipes.

Stray Current Corrosion caused by electricity flowing in from outside. Corrosion by direct current electricity proceeds faster than corrosion by alternating current electricity (when the capacity is the same, the rate of latter is 1/60~1/10,000 of that of the former).

In microscopically local attack the amount of corroded metal is very small which can cause considerable damage before being recognized with a naked eye. Although it happens in the part vulnerable to corrosion due to the crystal structure, it rarely spreads. Types of microscopically local attack are described below.

Intergranular corrosion occurs when the corrosion rate on the granular boundary of alloy is different from that inside the granule.

Stress Corrosion Cracking (SCC) occurs only when three particular conditions involving material, environment, and stress are met. A passive film is generally formed on the surface of a material of high corrosion resistance. Once the film is locally broken by an external factor, it becomes the starting point of pitting or stress corrosion cracking. As stress concentration increases locally, the inside solution contributes to the SCC spread and crack expansion. It usually occurs only to materials of high corrosion resistance.

Corrosion Fatigue is caused by interaction between erosion by corrosion and periodic stress or between rapidly repeating tension and compressive stress. Non-uniform stress on the screws of a pipe causes localized corrosion.

3.1.5 Soil Corrosion

3.1.5.1 Overview of Soil Corrosion

Soil corrosion refers to the corrosion of pipes, steel piles, storage tanks and power lines buried in soil. Corrosion in a soil environment follows the same principle as corrosion in an aqueous environment (moisture in soil works as an electrolyte). As for the difference between the two, the fluidity of corrosive chemical is high in an aqueous environment and low in soil.

3.1.5.2 Characteristics of Soil Corrosion

There are countless chemical, electrical, and mechanical factors that affect soil corrosion, including water content, aeration, resistivity, pH, ion concentration, microbial activity, stray current, and mechanical operation (such as stress). In addition, they work in mutually complex ways, which means that it is extremely difficult to understand soil corrosiveness accurately and that localized corrosion usually takes place.

The factors mentioned in Table 3.1 either affect corrosion independently or cause a corrosive reaction in combination of two or more.

Table 3.1 Major factors affecting corrosion

Factors	Related parameters	Results
Chemical factor	Moisture contents Dissolved oxygen pH Corrosive ion soil resistivity, etc.	Uniform Corrosion Pitting Corrosion
Microbial factor	Sulfur Reduced Bacteria (SRB)	Microbiologically Influenced Corrosion (MIC)
Electrical	Interference current [(Direct Current (DC)] or [(Alternative Current(AC)]	Electrolysis AC-induced corrosion
Mechanical	Operating pressure soil stress soil chemistry	Stress Corrosion Cracking Corrosion fatigue (SCC)

3.1.6 Soil Factor

Soil has a complex corrosive environment compared with the atmosphere, water, and other environments, which means that the corrosion rate of metal underground is rapid and very comprehensive. The corrosion rate of steel and cast iron pipes buried in the soil depends on the metal and soil factors. The corrosiveness of soil (electrolytes) is influenced by the their physical and chemical properties, meteorological conditions, including rainfall, temperature, and sunshine, and the laying conditions of other metals. Of such characteristics as soil composition, water content, aeration, soil pH, resistivity, dissolution component, microbial activity, and current, soil resistivity has the greatest impact on soil corrosiveness.

3.1.7 Internal Corrosion

The main kinds of pipe that are vulnerable to internal corrosion in water pipes are cast iron, steel, and copper pipes. There are many different causes to form such corrosion potential; the internal factors include metal composition, make-up, surface condition, internal stress, temperature difference, and non-uniform metal, and the external ones include the ion concentration of water that contacts the metal surface, dissolved oxygen, temperature, and velocity of moving fluid. When there are partial differences among them, a local battery is formed.

3.1.8 Corrosion Rate

Generally speaking, corrosion rate is fast in the early years of burial and tends to slow down with the passage of time. One should have measurements over a long period of time from years to dozens of years from the point of burial to the current point in order to accurately measure the corrosion rate, which is practically impossible. Thus the study assumed that the internal and external corrosion rate would remain the same until the current point like in the following expression by using the maximum internal and external corrosion depth and years of burial for Ductile Cast Iron Pipe (DCIP) and Cast Iron Pipe (CIP). Then it calculated the maximum corrosion rate in and outside the pipe as :

$$E_{mcr} = \frac{E_{mcd}}{y} \tag{3.6}$$

$$I_{mcr} = \frac{I_{mcd}}{y} \tag{3.7}$$

where, E_{mcr} = external maximum corrosion rate of pipe, mm/y; I_{mcr} = internal maximum corrosion rate of pipe, mm/y; and y = period of laying, year. A decrease in the pipe thickness is attributed to corrosion and can happen globally or locally.

Corrosion rate has been the subject of much controversy since a simple constant is assumed for the reduction rate of pipe thickness (Ahammed and Melchers, [26]; Romanoff, [37]).

The early corrosion rate models were the power law models for grey cast iron pipes. Of them, Romanoff's model [37]and Rossum's model [18] were representative. Romanoff's model proposed a power law model for maximum pit depth according to time based on the extensive data collection by of the United States National Bureau of Standards (NBS). The model is:

$$p_c = K \times time^m \tag{3.8}$$

where P_c : pit depth; K : a calibration coefficient for the dimensional relations of the model equation; m : constant in the range of 0<m<1. However, the Romanoff model assumes that the corrosion rate is infinite in the early days of laying and reaches “zero” after a long period of time. Rajani et al. [4] observed that a pipe life estimation method could underestimate pipe life. Romanoff [39], Rossum [18], Gummow [40], Dorn et al. [41], and Rajani et al. [4], among others, reported that the early corrosion rate is never infinite even though it is fast and that the corrosion rate reaches a normal state after a long period of time. Rossum [18] also proposed a model to estimate a pit outside the pipe according to soil characteristics based on the extensive collection of data. Rossum‘s model is expressed in the following equation with soil resistivity, pH, oxidation-reduction potential, and constant n related to permeability:

$$p_c = K_n K_a \left[\frac{(10 - pH)}{w} \right]^n T^n A^a \tag{3.9}$$

where Pc : pit depth; n : a permeability constant in the range of 0 to 1; pH : soil pH; w : soil resistivity (ohm-cm); A : the surface area of pipe exposed to the sun, m^2; Ka and a : constant; and according to pipe material; T : period of burial, year.

Rossum's model was based on the assumption that corrosion takes place in the range of pH 5 to 9. When pH is under 5, corrosion happens due to the liberation of hydrogen; and when pH is over 10, a cast iron pipe becomes passive. Those analyses by Rossum demonstrate that the possibility of maximum corrosion depth is greater than average corrosion depth.

Later Caproco Corrosion Prevention Ltd. [42] reported that soil resistivity is closely related to corrosion rate, only to fail to provide an explanation about correlations between them. O'day et al. [1] conducted a field study of the water pipes of PWD (Philadelphia Water Department), only to fail to reveal connections between soil characteristics and external corrosion. More recently, Rajani et al. [4] announced a two-phase model of a non-linear exponential form for soil characteristics and equation. Their two-phase model assumes corrosion rate at two phases; the first phase witnesses fast corrosion rate, and the second one a reduction and then linear rise of corrosion rate. The two-phase model takes into account a phenomenon of gradual inhibition of corrosion by corrosion products (iron oxide) after quick progress of corrosion in the early stage [26].

The model, however, was developed with the lack of enough information about the early days of burial and accordingly provides an unstable estimate pit depth (for the early days of corrosion, namely from 15 to 20 years).

$$t_{res} = t - (aT + b(1 - e^{-cT})) \tag{3.10}$$

where t_{res} : residual thickness, mm; t : early pipe thickness, mm; d : pit depth, mm; T : exposure time, year; and a, b, c : corrosion constant

3.2 Methods for Estimating the Life of a Water Pipe

In estimating the life of a water pipe, "rehabilitation" has been in a more general use than "life." When a water pipe reaches the end of life, it is replaced. When there is no structural problem with a water pipe that has not reached the end of life yet, it is restored through rehabilitation and has its life prolonged. Those are the ways decisions about water pipe rehabilitation have been made. In addition, based on estimation and analysis of corrosion,a range of methods have been developed in order to help to make a rehabilitation decision.

As regards estimation and analysis methods for making a decision about rehabilitation or life, there has been a focus on the development of a model to estimate the current or future state of a water network and determine a priority or rehabilitation time by considering the factors to affect the pipe conditions, such as water supply, water quality, and facility and the accident history, which is a major indicator to inform the deterioration of a water pipe.

3.2.1 Residual Strength

The influence of pit on the strength of a water pipe is usually assessed by the following two methods; one is to examine the mechanical characteristics of the undamaged material of each pipe, and the other is a precision structural analysis method to integrate the geometrical characteristics of the measured pit. These methods require analysis and evaluation according to the geometrical form of each measured pit. Usually adopted to conduct an integrated analysis of shapes, sizes, and boundary conditions of complex pits is the finite element method, which is applied to oil and gas pipes. Since the method requires a good amount of computation, it is not suitable for water pipes in practical terms, that is, it requires an enormous amount of effort and cost to be expanded and applied to water networks of hundreds of kilometers.

The second alternative is to assess the residual strength by applying a function to the sizes and geometrical characteristics of pits present in a pipe where stress is occurring. Here, strength means the strength of a vulnerable section due to pits rather than the strength of material. The old design method for new water networks was used to compare the major stress with the reduced resistance of the original pipe and determine the safety factor of the reduced pipe.

One of the differences between the two methods is the use of nominal stress rather than local stress. Nominal stress is calculated based on an assumption that there is no pit in the pipe and that nominal stress works on the beam, column, and ring or in a comprehensive manner. Local stress represents the intensive effects of stress due to the presence of pits. The use of nominal stress is particularly proper for experimental analysis.

The method is commonly used as a way to determine the residual strength of an oil or gas pipe (ASME, [43]), but ASME is applicable to steel pipes rather than cast iron pipes. For actual application, relations between the size of corrosive defect on a steel pipe and failure pressure must be established through hundreds of actual-size rupture tensile tests with actual samples. It is only natural that rupture tensile tests require enormous costs.

A range of mechanical tests, including tensile, four-point bending, and ring and fracture toughness have been used to assess the influence of defect size on water networks. These mechanical tests are also used to identify experimental correlations between strength and defect characteristics.

Flinn and Trojan [44] represented that pipe failure could occur due to many different elements even if the water pipe were operated within the stress limits and reported that pipe failure was related to fracture toughness. In general, failure is caused by stress in the presence of a discontinuous condition on a pipe as well as holes and cracks. Fracture toughness is a special defect that causes failure due to material characteristics.

A correlation equation between fracture toughness and fracture strength is as follows:

$$\sigma = \frac{K_{IC}}{Y\sqrt{\pi a_n}} \tag{3.11}$$

where K_{IC} : fracture toughness, psi; σ : nominal stress at fracture, psi; a_n : a measure of crack length, and; Y = a dimensionless correction factor that accounts for the geometry of the component containing the flaw.

Equation (3.11) not only offers information about the defect size of failure, but also presents the stress level against the standard. Pits on buried pipes in a corrosive condition can be considered as notches (grooves) in the wall. If a pit is semi-spherical, the reduction of pipe strength can determine the influence of a notch on material strength.

Rajani et al. [4] conducted assessment with samples of pit and spun cast iron pipes with pits or no pits and investigated the impact the dimension and geometric shape of a pit would have on the strength of a cast iron pipe. Their test samples contained pits in asmall area. They demonstrated a relation between nominal tensile stress and the dimension of pit:

$$\sigma_{tr} = \frac{\delta K_q}{\beta_d \left[\left(\frac{d_p}{t} \right) \sqrt{a_n} \right]^s} \tag{3.12}$$

where σ_{tr}: nominal tensile stress at which fracture is induced, MPa; K_q : provisional fracture toughness of the material, MPa; a_n : corrosion pit lateral dimension, orthogonal to the direction of applied stress, m; d_p : pit dimension; β_d: geometrical factor dependent on the dimension, orthogonal to the direction of applied stress; δ, s : factors to account for pit that are not "through or full penetration", shape and of ideal shape; and t : pipe net wall thickness, mm

3.2.2 Assessment of Failure Risk

3.2.2.1 Procedure for Assessment of Failure Risk

Pipes are manufactured to have a certain degree of strength to endure stress caused by load. The ratio between pipe strength and pipe stress is called the safety factor (SF). Pipe materials and thickness are designed and chosen to meet the SF requirements. Once a pipe is buried underground, the reduction in pipe thickness lowers pipe strength and then SF. Today, SF is used to assess failure risk and determine life expectancy.

Deb et al. [2] determined the point where Safety Factor (SF) becomes 1 as the criterion to assess the failure risk of water pipes since, theoretically speaking, the strength represented as pipe resistance against stress becomes smaller than stress caused by load at the point and accordingly cracks follow. Figure 3.2 shows a procedure to assess the failure risk of water pipes. The assessment consists of seven steps.

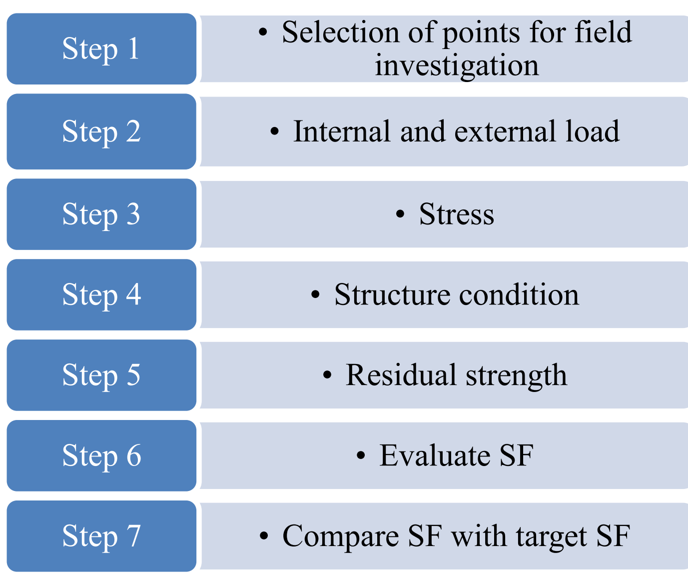


Figure 3.2 Procedure to assess the failure risk of water pipes [2]

Step 1 involves investigating factors that affect the deteriorating conditions of water pipes, including corrosion. They usually include water quality and soil factors that cause corrosion to water pipes.

Step 2 involves determination of internal and external load factors of the buried pipes and assessment of load. Those internal and external load factors include the following [2]:

1. Earth loads (W_e).
2. Traffic loads (W_t)
3. Frost loads (W_f)
4. Working water pressure (P_w)
5. Surge pressure/water hammer (P_s)
6. Expansive soil load (W_{exp})
7. Thermal expansion and contraction

Step 3 involves determination and calculation of stress on the pipes caused by internal and external loads. The following types of stress caused by internal and external loads are:

1. Circumferential stress
    - Circumferential stress caused by internal pressure (hoop stress) (σ_h)
    - Circumferential stress caused by external load (ring stress) ($\sigma_{\theta,total}$)
    - Circumferential stress that considers both internal pressure and external load (combined ring and hoop stress) ($\sigma_{h,\theta}$)
2. Longitudinal stress

- Longitudinal bending stress caused by external load (flexural stress) (σ_f)
- Longitudinal stress caused by internal pressure, temperature changes, and poisson rate (longitudinal stress) $(\sigma_{l,total})$

Total longitudinal stress considers the longitudinal and bending stress (flexural plus longitudinal stress) $(\sigma_{l,f} = \sigma_f + \sigma_{l,total})$ [2].

Step 4 involves an assessment of the structural conditions of pipes.

1. Decreases in pipe thickness and pits are measured:.
2. Risk of destruction and stress concentration are assessed due to pit growth.

Figure 3.3 shows analysis methods for pits in water pipes.

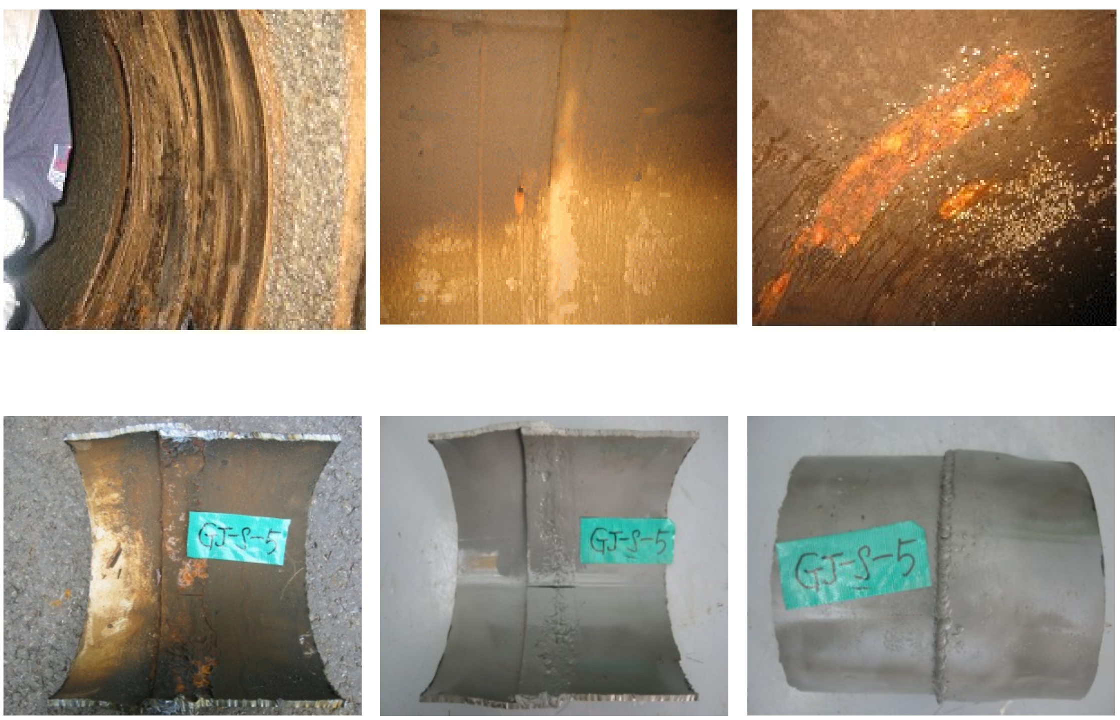


Figure 3.3 Analysis methods for pits in water pipes

Step 5 involves an assessment of the residual strength by corrosion [2]

1. Tensile strength
2. Compressive strength
3. Ring modulus of rupture
4. Modulus of rupture
5. Bursting tensile strength

Figure 3.4 Method for measuring the strength of water pipes

Figure 3.4 shows that strength tests with buried pipes are carried out according to test standards and sample standards.

Step 6 involves calculation of safety factor by comparing strength with stress caused by pipe load according to its structural conditions [2] :

1. Flexural safety factor (SF_f)
2. Ring safety factor (SF_θ)

3. Hoop safety factor (SF_h)
4. Longitudinal safety factor (SF_l)
5. Flexural plus longitudinal safety factor ($SFl_{,f}$)
6. Ring plus hoop safety factor (F)

Finally, step 7 involves comparison of SF of the buried pipe with the target SF and priority ranking of pipes according to the structural safety based on the comparison of results.

When such failure risk assessment is applied to pipe data, SF gets to be distributed wide either above 1 or below 1. If SF is above 1, one can conclude that the residual strength of the damaged pipe is over-measured or that the maximum load is under-evaluated. Those SF values can help predict the failure types of pipes.

The longitudinal failure occurs when SF is small for the stress caused by the simultaneous internal pressure and external load. Circumferential failure occurs when SF is small for the stress caused by longitudinal and flexural stress. In the case of leakage, such as a pinhole, the residual thickness of the pipe decreases, resulting in a small SF. In general, the leakage by a pinhole leads to a circumferential crack in the presence of excessive force.

3.2.3 Calculation of the Load of Failure Risk

Water pipes are under the influence of external load, such as earth load, truck load, and frost load. In areas that are subject to potential earthquake damage, pipes are designed earthquake-resistant by considering seismic load. For internal load, water pressure like working pressure and surge pressure is considered.

In Korea, only earth and truck loads are considered when designing water pipes. However, it is required to consider frost load and soil expansion load in addition to earth and truck load in Korea that records a high failure rate during winter. When a sub-zero condition lasts for hours, soil moisture is frozen to form an ice layer, which moves under the ground surface, freezes surrounding water, and increases vertical load onto the buried water pipe. Frost load can be chosen as a function of excavation width, frost depth, and soil characteristics [23]. Monie and Clark [45], Smith [46], DIPRA [47], and Field and Cohen [22] reported the earth pressure nearly doubled in winter due to frost load. It is also understood that expansion soil causes beam breaks through bending [48].

Issa [49] proposed a series of experiment equations through experiments to help estimate the swelling pressure based on the moisture content of soil.

Internal pressure includes working pressure that actually works on a pipe and surge pressure, causing hoop stress and longitudinal stress [50]. Working pressure means water pressure inside the pipe, and surge pressure causes a temporary change to pressure or flow under normal conditions of water pipe, which is called a transient hydraulic phenomenon. A transient phenomenon of fluid is called a surge or water hammer. The major causes of water hammer include changes to the valve setting (temporary or planned), start and stop of pump operation, and unstable pump or turbine characteristics [48]. The size depends on the degree of flow rate change, fluid density, and the speed of pressure wave in the water pipe. Surge pressure caused by a rapid loss of water heads in the pipe can be evaluated through the transmission speed of pressure wave.

3.2.3.1 Earth Load (General Excavation Applied) (W_e)

In general, the load upon the upper pipe equals the weight of the vertical soil layer projected onto the upper pipe. However, the load on the pipe from actual soil weight is affected by the relative stiffness of soil. In other words, soil shear resistance is conveyed to the earth pressure directly working on the upper pipe, which means that the actual load upon the buried pipe is smaller than the weight of the soil layer projected onto the upper pipe.

Most widely used to calculate earth pressure today is the Marston equation [51] which assumes that the entire weight of the soil column right above the excavated ditch is not conveyed to the pipe and that the load offsetting shear frictional force between the soil columns neighboring the excavation surface actually works on the pipe. Here the frictional shear force is determined by the relative sinking of earth pressure and is related to horizontal earth pressure. The Marston equation applies the Rankine equation [52] to horizontal earth pressure. In the Marston equation, one should usually consider (1) the depth of re-filling across the upper pipe, (2) the excavation width measured in the upper pipe, (3) the weight of earth used for re-filling, and (4) the frictional coefficient of re-filling earth. The Marston equation is:

$$W_e = C_d \gamma \ B_d \tag{3.13}$$

$$C_d = \frac{1 - e^{-(2K_\gamma \mu' \frac{H}{B_d})}}{2K_\gamma \mu'} \tag{3.14}$$

where W_e : earth pressure, kg_f/cm^2; C_d : a calculation coefficient; γ: unit weight of earth kg/cm^3(=0.0018 kg/cm^3); B_d : excavation width in the upper pipe, cm; e : natural logarithm constant; K_r : earth pressure coefficient of Rankine; θ: internal friction angle of re-filling earth (soil friction angle=30) and it is usually considered to be the same as that of the excavation slope, μ' : friction coefficient of re-filling earth and excavation slope ($\mu'= \tan\theta$), and H : height from the upper pipe to the ground surface(soil depth), cm.

The Marston equation is applied when it is general excavation or earth pressure is 2.0m or higher [53].

The Marston equation is usually applied when the pipe material is hard to consider in design from the perspective of pipe material. When the pipe material is soft, the pipe tends to experience ring defection for earth pressure. Thus they usually use the vertical equation that considers the weight of the vertical soil layer projected onto the upper pipe or vertical earth pressure. In the vertical equation, they consider no soil frictional force and assume that the weight of the soil in the upper pipe directly occurs on the pipe, ignoring lateral friction. Vertical earth pressure is expressed in Eq. 3.15 and also can be expressed like Eq. 3.16 when considering earth pressure [54].

$$W_e = \gamma H B_d \tag{3.15}$$

$$P_e = \gamma H \tag{3.16}$$

where W_e : vertical load, kg_f/linear cm; P_e : earth pressure, kg_f/cm^2; γ : unit soil weight, kg/cm^3; H : soil depth, cm; and B_d : excavation width, cm.

In Korea , the vertical equation is usually applied when it is vertical excavation according to braced wall construction, such as sheet piles or burial depth is 2.0m or less [53]. In such a case, excavation width is not taken into consideration. In the U. S. A., they apply the Marston equation to rigid pipes, such as cast iron pipes and the vertical equation to flexible pipes such as ductile cast iron pipes and steel pipes instead of considering burial depth or construction method.

3.2.3.2 Traffic Load (Application of the Dispersion Angle Method) (W_t)

Traffic load is transient load referring to the load caused on a pipe buried shallow by trucks, trains, or other types of vehicle. It is under the influence of vehicle weight, tire pressure and size, vehicle speed, surface roughness , road pavement volume and type, soil type, and distance from the point where load is generated and the buried pipe. There are two common ways to calculate pressure caused by traffic load: one is the most universal and only considers traffic load as concentrated load; and the other is to consider distributed load over an area contacting the ground wheel. Boussinesq [55] calculated stress distribution within a semi-infinite elastic medium by load on a point on the surface, and Hall and Newmark [56] calculated the Boussinesq equation with integral calculus to obtain a load coefficient.

KWWA [53] define traffic load as rear wheel load and ignore front wheel load. The dispersion angle method is used to calculate load strength upon the pipe. While the tire tread width for the vertical direction of road is dispersed over 20~45m, the occupied width in the horizontal direction is dispersed over 1.75m. An impact factor is also used to consider load according to burial depth. Table 3.2 shows impact factors according to burial depth.

$$W_t = \frac{2nP_{rw}(1+i)}{\left[nL+(n-1)\cdot C+b+2H\tan\theta\right](a+2H\tan\theta)} \tag{3.17}$$

where W_t: external pressure by truck load, kg_f/cm^2; P_{rw}: rear wheel(one wheel) load of the truck, kg; n : number of trucks aligned along the occupied width; L : interval from the center of the rear wheel (generally 175cm); C : interval among the rear wheel centers of neighboring trucks (generally 100cm); b : rear wheel tread width (cm) (generally 50cm); θ : dispersion angle (°) (generally 45°); a : wheel tread field (cm) (generally 20cm); i : impact factor; and H : height between the upper pipe to the ground (soil depth), cm. Table 3.3 shows rear wheel load of vehicle on each bridge grade.

Table 3.2 Relationship between soil depth and impact factor

Soil depth, m	Impact Factor (i)
$H \leq 1.5$	0.5
$1.5 < H < 6.5$	0.65 – 0.1H
$H > 6.5$	0

Table 3.3 Rear wheel load of vehicle

Bridge grade	Truck	Overall load(ton)	Front wheel load(kg)	Rear wheel load(kg), P_{rw}
1	DB-24	43.2	2,400	9,600
2	DB-18	32.4	1,800	7,200
3	DB-13.5	24.3	1,350	5,400

3.2.3.3 Expansion Soil Load (W_{exp})

Soil expansion can generate important stress for buried pipes, but there is no definite standard or methodology to measure expansive soil load upon buried pipes. According to CIPRA, expansive soil is the soil that expands when wet and contracts when dry. Expansive soil is generally clay soil whose particles are smaller than 1~2 microns. One can distinguish expansive soil as follows [2]:

- Soil becomes hard and develops cracks when dry.
- Soil is very sticky when wet.
- Soil can freely change its form or shape with high water content.
- Soil feels sleek between fingers.
- Soil contains minute particles as sand or large, rough earth.
- It is clay soil.

Such expansive soil is known to cause beam breaks. Issa [49] proposed the following equation after conducting an experiment to predict swelling pressure based on the water content rate of soil:

$$W_{\exp} = \alpha_1 \left(\omega_L - 46 \right) \quad \text{when } 9.4\% \leq \omega_0 \leq 16.2\% \tag{3.18}$$

$$W_{\exp} = \alpha_2 \left(\omega_L - 56 \right) \quad \text{when } 21.4\% \leq \omega_0 \leq 27.5\% \tag{3.19}$$

$$W_{\exp} = \alpha_3 \left(\omega_L - 77 \right) \quad \text{when } 32.5\% \leq \omega_0 \leq 33.1\% \tag{3.20}$$

where α_1 : 0.30 kg_f/cm^2; α_2, α_3: 0.25 kg_f/cm^2; w_L : liquid limit(v/v)%; w_o : initial water content in soil, % ; and W_{exp} : swelling pressure, kg_f/cm^2.

3.2.3.4 Frost Load (W_f)

When the atmosphere condition continues under zero for hours, water in soil becomes frozen and creates an ice layer, which then moves to the lower part of soil, freezes water there, and continues until soil equilibrium. The freezing layer at the lower part of the ice layer generates pressure as ice grows (volume) and expands. Such swelling pressure increases the vertical load on the buried pipe. Smith [46] reported that load increases by about two times in the deepest frost layer. The high failure frequency of water pipes during winter is attributed to increased earth pressure by frost load upon the buried pipes. In the U. S. A. and Korea, they do not consider frost load when determining earth pressure or traffic load in design. Rajani et al. [4] calculated frost load by multiplying earth pressure. The multiplication value ranges from 1 - 2. It is 1 when there is no frost load and 2 when maximum frost load is assumed.

3.2.3.5 Internal Pressure (P_{total})

Internal pressure causes circumferential and longitudinal stress, working on the pipes (hydrostatic pressure and surge pressure). There are two types of internal pressure; one is working water pressure (*Pw*) and surge (*Ps*), which can be calculated using the following equation:

$$h = \frac{\alpha V}{g} \quad \text{or} \quad P_s = \left(\frac{a}{g}\right)\left(\frac{spgr}{1000}\right) V \tag{3.21}$$

where, h : surge pressure, cm; g : acceleration due to gravity, 980 cm/s^2; V : maximum flow change, cm/s (60.96 cm/s, CIPRA handbook); $spgr$: water gravity(water = 1.0); and a : propagation speed of pressure wave, cm/s.

The speed of surge pressure wave is affected by the characteristics of pipe and fluid. The pipe characteristics include (1) elasticity coefficient, (2) inside diameter, and (3) thickness; and the fluid characteristics include (1) elasticity coefficient, (2) density, and (3) air volume. When considering those characteristics, the following equation is obtained:

$$a = \frac{4600 \times 30.48}{\sqrt{(1 + \frac{kd}{Et})}} \tag{3.22}$$

where, k : elasticity coefficient of fluid (water), 2.1×10^4 kg_f/cm^2; E : elasticity coefficient, kg_f/cm^2 ; and d : inside diameter of the pipe, cm.

3.2.3.6 Thermal Expansion and Contraction

Generally speaking, most objects grow in volume as temperature rises because atoms and molecules become active and increase in vibration, resulting in a growing distance among them. The parts whose temperature is higher than the surrounding environment tend to expand, and the parts whose temperature is lower than the surrounding environment tend to control expansion. If free expansion and contraction are possible, there will be no stress caused by heat. When free heat transformation is hindered by a surrounding object or area, the hindered stress increases thermal stress inside the object.

Water pipes buried underground are subject to the restriction of surrounding soil and get hindered in free thermal transformation (distance change=0), in such a case thermal stress occurs. The pipe walls contract due to temperature changes by resistance against surrounding soil and generate tensile stress in winter and compressive stress according to rising temperature and expansion in summer. As a result, tensile stress causes cracks on the pipe surface and pipe bursting in winter. Since water pipes are more vulnerable to tensile stress than compressive stress, tensile stress should be considered more importantly.

Table 3.4 Physical characteristics of each pipe type

Type	Linear expansion coefficient(α)	Elasticity coefficient(E)	Poisson Ratio
CIP	10×10^{-6}	1×10^{5}	0.25
D(C)IP	$11(9.9\sim12)\times10^{-6}$	1.68×10^{6}	0.28
SP	14×10^{-6}	2.1×10^{6}	0.30
PVC	54×10^{-6}	2.8×10^{4}	0.38
PE	144×10^{-6}	7.7×10^{3}	0.35

Longitudinal stress according to long-term temperature changes can be calculated as:

$$\sigma_{l,\Delta T} = E\alpha\Delta T \tag{3.23}$$

where $\sigma_{l,\Delta T}$: longitudinal stress according to temperature increase, kg_f/cm^2; E : elasticity coefficient of the pipe, kg_f/cm^2; α : linear expansion coefficient, cm/cm/°C; and ΔT : temperature change, °C. Table 3.4 shows physical characteristics of each pipe type.

3.2.4 Calculation of Stress on Water Pipes

The design standards or manuals offer detailed descriptions of stress on water pipes according to the types of pipe. In Korea, there are design standards for each type of pipe (DCIP, SP, PVC, PE, etc.) by considering such stress so that stress on each type of pipe can be considered to determine pipe thickness. The study only examines cast iron and steel pipes most used today [53].

3.2.4.1 Cast Iron Pipe (CIP)

3.2.4.1.1 Circumferential Stress by Internal Pressure

There is circumferential stress on water pipes by internal pressure; in such a case, the pipes should have the minimum pipe thickness to endure circumferential tensile stress. Circumferential stress by internal pressure can be calculated with hydrostatic pressure, working pressure, or surge pressure. By combining those kinds of stresses, one can also obtain the total hoop stress:

$$\sigma_h = \frac{P_{total} d}{2t} = \frac{\left(P_s + P_d\right) d}{2t} \tag{3.24}$$

where, σ_h : circumferential stress by internal pressure, kg_f/cm^2; t : pipe thickness, cm; d : inside diameter of the pipe, cm; and P_{total} : total internal pressure, kg_f/cm^2; P_w: working water pressure; and P_s : surge pressure.

3.2.4.1.2 Bending Stress by External Pressure

Korea Water Work Association [53] defines bending stress on cast iron pipes caused by external load as:

$$\sigma_{\theta,d} = \frac{M_e + M_t}{Z} \tag{3.25}$$

where $\sigma_{\theta,d}$: bending stresses; M_e: bending momentum by earth pressure; M_t : bending momentum by traffic load; Z : section coefficient of the pipe unit width, Z : $t^2/6$ (cm^2), and t : pipe thickness (cm)

The earth pressure and traffic load, respectively, can be computed with bending momentum as follows:

$$M_e = K_f W_e R^2 \tag{3.26}$$

$$M_t = K_t W_t R^2 \tag{3.27}$$

where K_t : coefficient determined by the supporting angle at the pipe bottom; K_t : the upper pipe: 0.076, the pipe bottom: 0.011; and R : pipe radius, cm = $D_m/2 \fallingdotseq d/2$. Table 3.5 shows coefficients by the supporting angle at the pipe bottom.

Table 3.5 Coefficient determined by the supporting angle at the pipe bottom (CIP)

Bottom / Location	40°	60°	90°	120°	180°
Upper pipe	0.140	0.132	0.121	0.108	0.096
Pipe bottom	0.281	0.223	0.164	0.122	0.096

To conclude, the bending stress on cast iron pipes by the external load can be expressed as:

$$\sigma_{\theta,d} = \frac{6(K_f W_e + K_t W_t)R^2}{t^2} \tag{3.28}$$

3.2.4.1.3 Tensile Stress

The bending stress is considered as tensile stress and multiplied by 0.7 for ductile cast iron pipes in the design stage, which means there should be a safety assessment:

$$\sigma_{h,\theta d} = \sigma_h + 0.7\sigma_{\theta,d} \tag{3.29}$$

3.2.4.1.4 Strain

The strain proposed by Watkins and Spangler [57] is usually considered for ductile cast iron pipes. Korea Water Work Association [53] limits strain within 3% by considering exfoliation by cement mortar. Eq 3.28 considers earth pressure and traffic load for external load. The American Water Work Association [58] proposes 1~1.5 for defection lag factors, but Korea Water Work Association [53] applies 2, as seen below:

$$\Delta X = \frac{2K_x\left(W_{total}\right)R^4}{EI + 0.06146 \cdot E'R^3} < 3\% \tag{3.30}$$

where ΔX : strain volume of the pipe body in horizontal direction, cm; D_l : defection lag factor(generally 1~1.5 in AWWA M41, and 2.0 in Korea*)*; W_{total} : W_e+W_t, kg_f/linear cm^2; R : average radius of the pipe (=Dm/2=d/2), cm; EI: pipe wall stiffness, kg_f-cm; E : pipe elasticity coefficient, kg_f/cm^2; I : sectional secondary moment per unit width of the pipe, cm^3 (t = pipe thickness); K_x : horizontal strain coefficient determined by supporting angles (generally 0.089); and E': reaction coefficient of earth, kg_f/cm^2. Table 3.6 shows standard burial conditions of pipes.

Table 3.6 Standard burial conditions of pipes [58].

Type of burial	Content	E', psi (kg_f/cm^2)	Initial supporting angle	K_b	K_x
Type 1	The bottom is excavated even and re-filling is grounded loose.	150 (10.5)	30	0.235	0.108
Type 2	The bottom is excavated even, and re-filling is grounded light and fixed at the center of the pipe.	300 (21.0)	45	0.210	0.105
Type 3	Minimum soil should be used to make the foundation loose until 4 inches in the lower pipe. Re-filling is grounded light and fixed at the upper pipe.	400 (28.1)	60	0.189	0.103
Type 4	The foundation is grounded until 1/8 of the pipe diameter or 4 inches in the lower pipe with sand and gravel. Re-filling is grounded hard until the upper pipe. (Roughly, the standard proctor suggests 80%, AASHTO T-99.)	500 (35.1)	90	0.157	0.096
Type 5	A foundation is built with granular material until the center of the pipe or minimum 4 inches. It is grounded till the upper pipe with granular or selected material. (Roughly, the standard proctor suggests 90%, AASHTO T-99.)	700 (49.2)	150	0.128	0.085

Consideration of the pipe-zone embedment condition included in this table may be influenced by factors other than pipe strength. Additional information is given in ANSI/AWWA C600 [59]. For pipe 14 inches and larger, consideration should be given to the use of laying conditions other than type 1. Granular materials are defined per the AASHTO Soil Classification System [60] or the United Soil Classification System [61], with the exception that gravel bedding/backfill adjacent to the pipe is limited to 2 inches maximum particle size per ANSI/AWWA C600 [60]. Flat-bottom is defined as undisturbed earth. Loose soil or select material is defined as native soil excavated from the trench, free of rocks, foreign material, and frozen earth. In order to estimate moisture density relations of soils, the rammer of 5.5 pounds rammer drop into 12 inches. Figure 3.5 shows that standard burial conditions for each type of pipe.

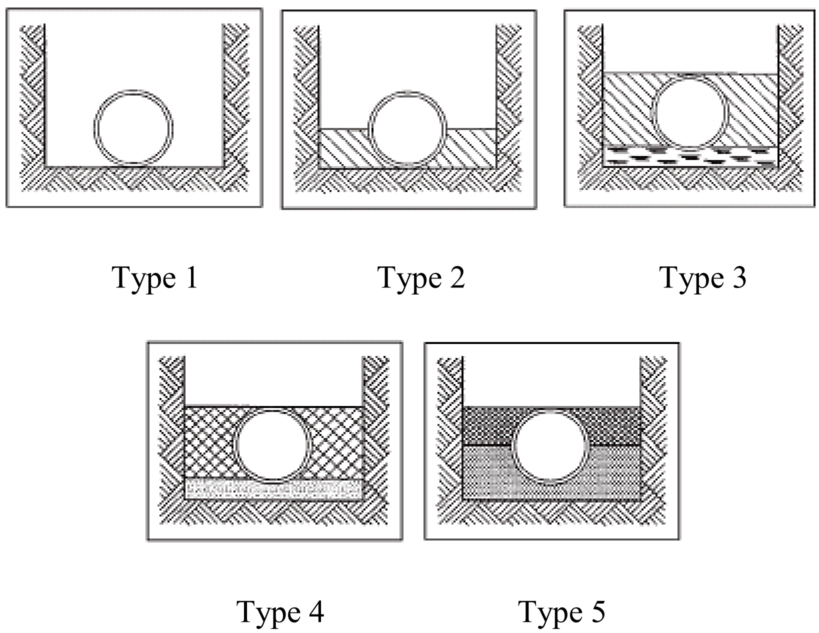


Figure 3.5 Standard burial conditions for each type of pipe [58]

3.2.4.2 Steel Pipes

3.2.4.2.1 Circumferential Stress by Internal Pressure

There is applied for circumferential stress by internal pressure just like cast iron pipes.

3.2.4.2.2 Bending Stress by External Load

For Steel Pipes, Korea Water Work Association (KWWA) considers such types of external load as earth pressure and traffic load and determines thickness by considering strain by those types of load and bending stress on the lower pipe (Water Supply Facilities Standards, 2007). In such a case, the bending stress can be obtained as follows:

$$\sigma_{\theta,s} = \frac{2}{fZ}(W_e + W_t) \times \frac{K_b 2EI + (0.06146K_b - 0.08313K_x)E'R^5)}{EI + 0.06146E'R^3} \tag{3.31}$$

where, $\sigma_{\theta,s}$: bending stress by external load in the lower pipe; f : form coefficient, 1.5; Z : sectional coefficient of the unit pipe width, $Z = t^2/6$ (cm^2), t : pipe thickness(cm); W_e : earth pressure, kgf/cm^2; W_t : traffic load, kgf/cm^2; R : average radius of the pipe, $(D_m/2 = d/2)$; E : elasticity coefficient of the pipe, kgf/cm^2; I : sectional secondary moment per unit pipe width, $I = t^3/12$, cm^3; E' : reaction coefficient, kgf/cm^2; and K_b : bending moment coefficient at the pipe bottom determined by supporting angles. Table 3.7 shows coefficients determined by the initial supporting angles of the pipe (SP).

Table 3.7 Coefficients determined by the initial supporting angles of the pipe (SP)

Initial supporting angle	K_b	K_x	$(0.061K_b\text{-}0.083K_x)$
60°	0.189	0.103	0.00307
90°	0.157	0.096	0.00171
120°	0.138	0.089	0.00107
150°	0.128	0.085	0.00082

3.2.4.2.3 Strain

It is the same as eq 3.30. The Water Supply Facilities Standards limits the strain of steel pipes within 5% by considering wrapping coating.

3.2.4.3 Calculation of Safety Coefficient According to Failure Risk Assessment

There are various kinds of stress occurring in water pipes according to internal and external loads. Pipes can prevent bursting by having greater strength than stress. Deb et al. (2002) proposed six safety coefficients for grey cast iron pipes. There are six safety factors related to stress: flexural stress safety factor, ring stress safety factor, hoop safety factor, longitudinal safety factor, flexural plus longitudinal safety factor, and ring plus hoop safety factor.

In the Korean Facilities Standards, however, these same safety coefficients cannot be applied to all types of pipes except for grey cast iron pipes. Since failure types and forms are different among types of pipe, different types of load and stress should be considered for each type of pipe. Table 3.8 shows criteria of failure risk based on corrosion depth or safety factor (SF).

Table 3.8 Estimation criteria of pipe condition for rehabilitation [62]

Pipe	Grade	Rehabilitation plan	Criteria	Condition of CML	Method of investigation
CIP /DIP	Ⅲ	Renovation	◦ Percentage of corrosion depth : less than 50% ◦ Safety factor for internal or external pressure : 2.5 < SF		Analysis of pipe body
	Ⅳ	Renovation or replacement	◦ Percentage of corrosion depth: 50~65% ◦Safety factor for internal or external pressure: 1.0 < SF ≤ 2.5		
	V	Replacement	◦ Percentage of corrosion depth: more than 65% ◦ Safety factor for internal or external pressure: SF ≤ 1.0 ◦ Percentage of external corrosion depth in all grade: more than 50%		
Pipe	Grade	Rehabilitation plan	Criteria	Condition of CML	Method of investigation
DCIP	I	Can be used on end	◦ Slime accumulation on the CLM surface	◦ CML is good condition : Neutralization less than 100% ◦ No impact of water quality(turbidity, foreign substance, and appearance of red water)	Endoscope

Table 3.8 Continued

Pipe	Grade	Rehabilitation plan	Criteria	Condition of CML	Method of investigation
DCIP	II	Cleaning	◦ Slime accumulation on the CLM surface	◦ Deterioration of CML in function : Neutralization less than 100% ◦ Some impact of water quality(turbidity, foreign substance, and appearance of red water)	
DCIP	Ⅲ	Renovation	◦ Percentage of corrosion depth : less than 50% ◦Safety factor for internal or external pressure: 2.5 < SF	◦ Loss of CML anti-corrosive function : Progress of internal corrosion	Analysis of pipe body
	IV	Renovation or replacement	◦ Percentage of corrosion depth: 50~65% ◦Safety factor for internal or external pressure : 1.0 < SF ≤ 2.5	◦ Loss of CML anti-corrosive function : Progress of internal corrosion	Analysis of pipe body Endoscope
	V	Replacement	◦ Percentage of corrosion depth: more than 65% ◦Safety factor for internal or external pressure: SF ≤ 1.0 ◦ Percentage of external corrosion depth in all grade: more than 50%	◦ Loss of CML anti-corrosive function : Progress of internal corrosion	

Table 3.8 Continued

Pipe	Grade	Rehabilitation plan	Criteria	Condition of CML	Method of investigation
	I	Can be used on end	◦ Slime accumulation on the surface of inside coating material	◦ Good condition of inside coating material : No impact of water quality(turbidity, foreign substance, and appearance of red water)	
SP Pipe	II	Cleaning	◦ Slime accumulation on the surface of inside coating material ◦ Percentage of corrosion depth: less than 35%	◦ Deterioration of anti-corrosive function in inside coating material lining : Percentage of peeling less than 10% : Some impact of water quality(turbidity, foreign substance, and appearance of red water)	Endoscope Method of investigation

Table 3.8 Continued

Pipe	Grade	Rehabilitation plan	Criteria	Condition of CML	Method of investigation
SP Pipe	III	Renovation	◦ Percentage of corrosion depth: less than 35% ◦Safety factor for internal or external pressure: 2.5 < SF	◦ Deterioration of anti-corrosive function in inside coating material lining : Percentage of peeling more than 10%	
SP	IV	Renovation or replacement	◦ Percentage of corrosion: 35~50% ◦Safety factor for internal or external pressure: 1.0 < SF ≤ 2.5	◦ Deterioration of anti-corrosive function in inside coating material lining : Percentage of peeling more than 10%	Analysis of pipe body
	V	Replacement	◦ Percentage of corrosion depth: more than 50% ◦Safety factor for internal or external pressure: SF ≤ 1.0	◦ Loss of anti-corrosive function in inside coating material lining : Percentage of peeling more than 10%	Analysis of pipe body

For cast iron pipes of 200mm or under and steel pipes of 300 mm or under, the decision of grade III~V is based on the percentage of corrosion depth. In addition, the safety factor can be taken into account. Once the pipe diameter exceeds those criteria, the safety factor should be taken into account.

Percentage of corrosion depth represents maximum internal (p_{ic}) and external (p_{ec}) corrosion depth divide actual pipe thickness. where, p_{ec} : maximum external corrosion depth; p_{ic} : maximum internal corrosion depth. When the SF of a steel pipe is 2.5 or lower under the influence of internal and external load in the original design, the steel pipe will be graded "II" or higher if the peeling percentage of internal and external coating material is acceptable. The decision of cleaning will be made based on the direct influence of field study.

3.2.4.4 Determination of Physical Residual Life

In general, old water pipes are replaced with new ones in sections when the repair costs exceed a certain limit. For instance, replacement is done when the number of failures during a certain period of time exceeds a set limit or a water pipe reaches the end of its set life. The former period of time is called service life, the latter, and useful life.

The general service life of a water pipe ranges from 60 to 100 years, which is an experience value that does not count certain elements or the condition of local sections [1].

The structural strength of a water pipe is damaged by corrosion over the course of service life. Early studies on corrosion affecting pipe strength mostly concerned gas pipes rather than water pipes. In the early 1970s, the American Gas Association Pipeline Committee (AGAPC) developed a method to estimate the pressure strength of pipes with corrosive defects of various sizes and set the ASME [63] standard based on its esearch efforts. Today ASME [63] is used as a manual to determine the residual strength of a pipe that is subject to corrosion under internal pressure.

The method suggested in ASME [63] standard was designed to assess residual strength after metal loss based on an experimental, semi-empirical approach and is limited to a single pipe defect under the influence of internal pressure. Recent studies have proposed new models comparable to ASME [63] and the new models are capable of analyzing a good number of complicated corrosion defects with longitudinal load combined with bending load. Developed by Battelle Company, the ReSTRENG (Remaining STRENGth) software can conduct more detailed analysis of corrosion defects. This program reduces some assumptions, which set limits to the ASME [63] standard, and uses a detailed geometrical map of corrosion.

Problems with water pipes have been neglected for considerable parts so far, but assessments have been made of various corrosion phenomena and physical characteristics of cast iron pipes. For example, National Research Center of Canada (NRCOC) recently developed a method to assess the residual life of cast iron pipes based on experimental investigations and demonstrated the impacts of corrosion on the structural strength of water pipes in the process. The method can estimate residual capacity as well as the point when the safety factor of each pipe section drops to a set limit 1 by evaluating the size of a pit.

Rajani et al. [4] gathered data about equations, mechanical characteristics, stress caused by internal and external load, corrosion rate, operational conditions, and design standards for each water pipe to implement the model. They also assessed residual tensile strength according to the sizes and mechanical characteristics of pits and suggested failure conditions of a pipe, which were expressed in a failure interaction curve that considered hoop stress caused by internal and external stress and the results of longitudinal stress on the pipes based on an assumption that a pipe is subject to failure. The two following equations must be met to prevent urgent failure to the pipe. Here, σ_t is the uniaxial tensile strength of the pipe material:

$$\left(\frac{\omega}{W}\right)+\left(\frac{p}{P}\right)\leq 1.0 \tag{3.32}$$

$$\frac{\sigma_l}{\sigma_t}\leq 1.0 \tag{3.33}$$

This study represented the followings to obtain SF to determine rehabilitation priorities:

First, this study included how to calculate corrosion depth of pipes; secondly, included how to calculate residual strength and load to learn the life of pipe; finally, included the criteria of pipe condition for rehabilitation.

4. PHYSICAL FAILURE RISK MODEL

This study measured corrosion thickness with the collected pipe bodies, predicted corrosion growth rates based on the corrosion thickness measurements with a linear, exponential, and power model, assessed the lining conditions of pipes, and predicted the residual strength of each CIP, DIP and SP according to corrosion depth.

4.1 Directions for Model Development

Assessment of failure risk of metal water pipe is useful for determining the priority of rehabilitation by evaluating which pipe section has a high risk of failure. Such an assessment of failure risk, however, provides no information about when the pipe will be damaged, while it does show the failure risk of each pipe. Thus, a new model should be developed by combining assessment of failure risk with a model for the estimation of residual life, as shown in Figure 4.1 in order to estimate when the pipe will be damaged and what its residual life will be.

One can estimate residual life by assessing stress on the pipe itself caused by load, estimating failure risk at the current point with a model estimating residual thickness and strength, and predicting changes to residual thickness and strength according to time and further to the safety factor. Since there are no big changes to the environment after laying, there will be no big changes to load. Given that stress increases according to changes to residual thickness, estimation for stress according to changes to residual thickness must be accompanied.

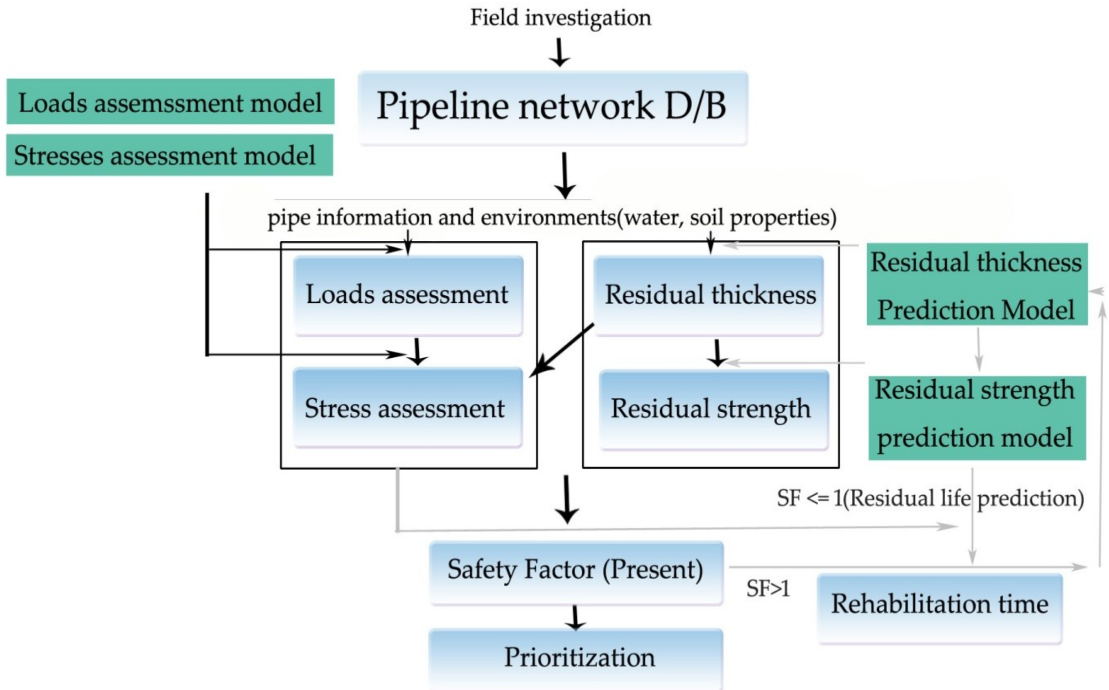


Figure 4.1 Model for structural safety and residual life on buried water pipes

In non-metal water pipes, corrosion does not cause loss of strength, but the deterioration of the material itself causes brittleness to rise, which needs to be determined in advance. There are no standardized methods to calculate load or stress according to different types of pipes. Different assessment methods have been proposed in the literature. Thus, a realistic assessment method should be implemented.

A water pipe will reach the end of its life when the safety factor drops to 1 or lower as in the failure criteria as

$$SF = \frac{-\left(\frac{p}{P}\right)+\sqrt{\left(\frac{p}{P}\right)^2+4\left(\frac{w}{W}\right)^2}}{2\left(\frac{w}{W}\right)^2} < 1 \tag{4.1}$$

$$SF = \frac{\sigma_{res}}{\sigma_{h,\theta d}} < 1 \tag{4.2}$$

Thus, it is assumed that a water pipe will reach the end of its life when the safety factor drops to 1 or lower by taking into account the hoop safety factor based on internal and external loads and that of bending and longitudinal stress to implement a predicable structure based on findings.

Figure 4.2 presents an algorithm for estimation of the residual life of water pipes based on those criteria of judgment. In the figure, the safety factor at the current point is predicted by estimating the current residual thickness and strength with a model for estimation of residual thickness and strength. When the safety factor is 1 or lower, the pipe is thought to have reached the end of its life. When it is greater than 1, residual life is the time till it drops to 1 by estimating its changes according to time ($T_P + i$, i=1, 2, 3.., n). If the time of laying is To, the current time for assessment is T_P, and if the time till the safety factor drops to 1 is $T_p + n$, the life expectancy (L_T) and residual life (RL_T) of the pipe can be expressed as

$$L_T\left(Age\ of\ pipe\right) = T_p + RL_T = (T_{p+n}) \tag{4.3}$$

In Figure 4.2, stress assessments according to changes in residual thickness are excluded along with residual thickness when it is a non-metal water pipe.

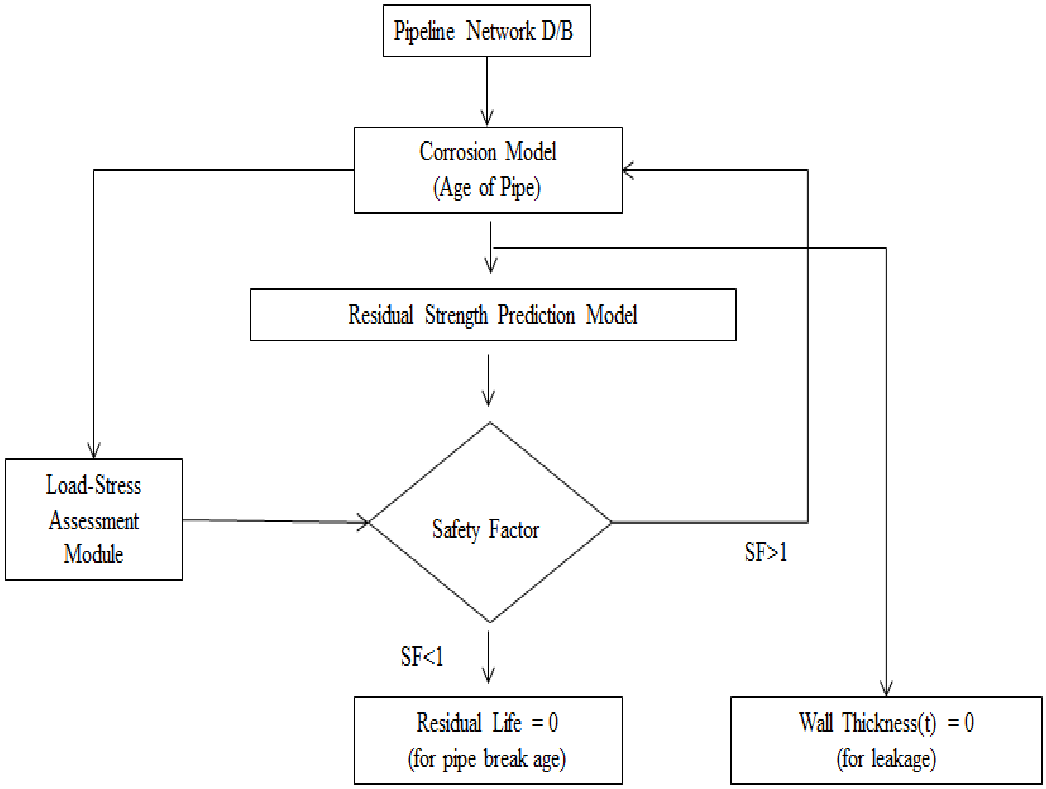


Figure 4.2 Structure of an algorithm for estimation of residual life of a water pipe (a metal water pipe)

4.2 Development of a Model

The following sections will address the development of models based on the discussions above. First, the corrosion depth and rate of cast iron pipes and steel pipes will be covered, followed by an examination of corrosion rate models.

In order to develop a model for estimation of residual life of a metal water pipe according to deterioration, the metropolitan and local water pipes of K-Water from 2001 to the present were examined and findings on residual thickness, residual strength (metal), CML neutralization, and exfoliation of coating materials based on the collected data (from 178 points along the water pipes) were gathered.

4.3 Estimation Model for Residual Thickness

Corrosion has a huge influence on the deterioration of water pipes in the operation process after laying and is a major cause of pipe failure, which is why many investigators have quantified the impact of such influential factors on pipe deterioration and have attempted to assess the conditions for deterioration of water pipes. In Korea, it has been found that many different factors cause corrosion in water pipes. However, not enough efforts have been made to assess the influence of various factors and evaluate the conditions for the deterioration of water pipes, likely because it is difficult to assess all the factors that affect the corrosion of water pipes in a quantitative manner. Thus this study developed a model for corrosion growth based on changes to internal and external corrosion depth according to the years of laying and obtained the following results with data collected through the prevention and inspection activities of K-Water.

4.3.1 Maximum Internal and External Corrosion Depth

Figures 4.3 and 4.4 show the results of measurement of maximum internal and external corrosion depth of cast iron pipes (CIP/DIP/DCIP) and steel pipes according to the years of laying, respectively. Figure 4.3 shows a very wide range of maximum external corrosion depth (p_{ec}) of cast iron pipes from 0.0 to 7.12 mm with an average of 1.64 mm. The cast iron pipes recorded an average 3.07mm of maximum internal corrosion depth (p_{ic}) in the range of 0~9.47 mm, which is 1.87 times higher than 1.64mm of p_{ec}. When there is a cement mortar lining (CML) inside DCIP, p_{ic} becomes 0 due to the anti-corrosive effects of CML. The oldest pipe bodies of DCIP with a CML were laid in 1983 and 1984 and have suffered no internal corrosion so far, which means the anti-corrosive effects of CML seems to last at least for 25 years. When there is no CML inside CIP or DIP, those cast iron pipes undergo failure due to internal corrosion. When there is CML inside DCIP, external corrosion is to blame.

In Figure 4.4, the steel pipes are coated in and outside in most cases unlike cast iron pipes. Internal and external corrosion starts only after coating is peeled off. The internal and external corrosion depth of steel pipes in the figure represents the corrosion depth of a section where the coating material was peeled off. All the measured steel pipes had 0mm of external corrosion except for eight that were laid around 1985 whose external corrosion was in the range of 0.5~2.38 mm. At the time of measurement, more than 93% of steel pipes that had been buried for 36 years had their external coating materials kept intact.

The maximum internal corrosion depth was 6.1mm as internal coating materials were peeled off in some of the steel pipes buried between 1965 and 1990. The percentage of coating material exfoliation was higher in internal coating materials than in external ones. Thus the major factors of steel pipe failure seem to be the exfoliation of internal coating materials and resulting internal corrosion as internal coating materials first come off and lead to corrosion before external ones.

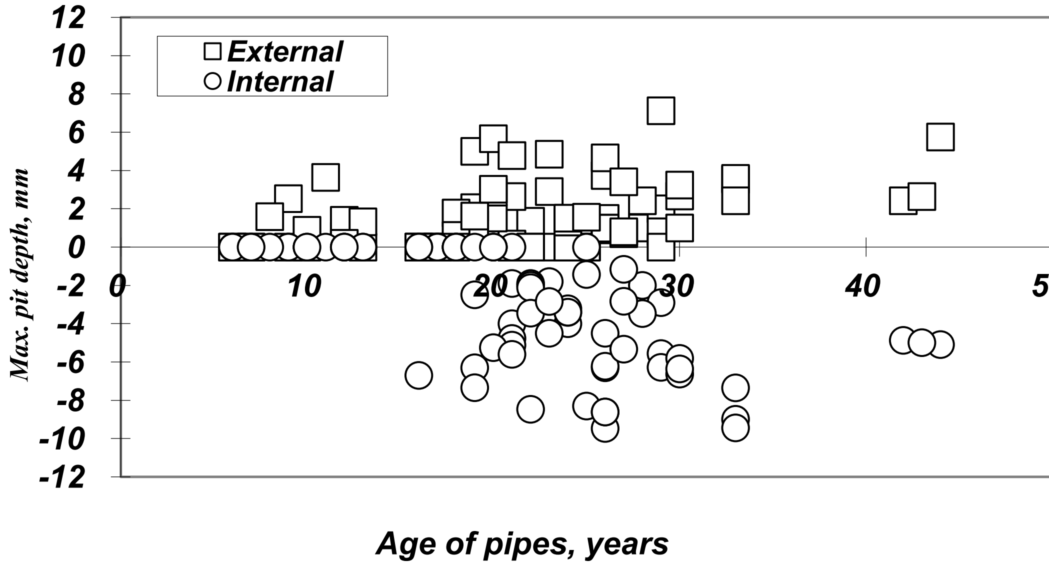


Figure 4.3 Measurements of p_{ec} and p_{ic} according to years of laying (DIP/DCIP)

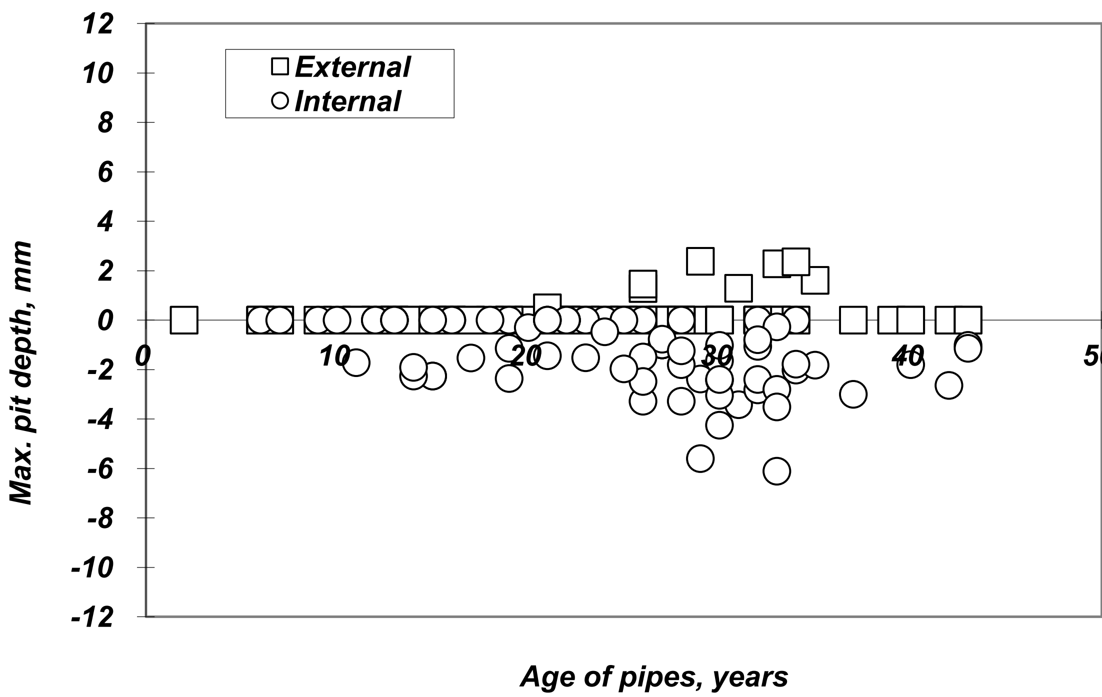


Figure 4.4 Measurements of p_{ec} and p_{ic} according to years of laying (SP)

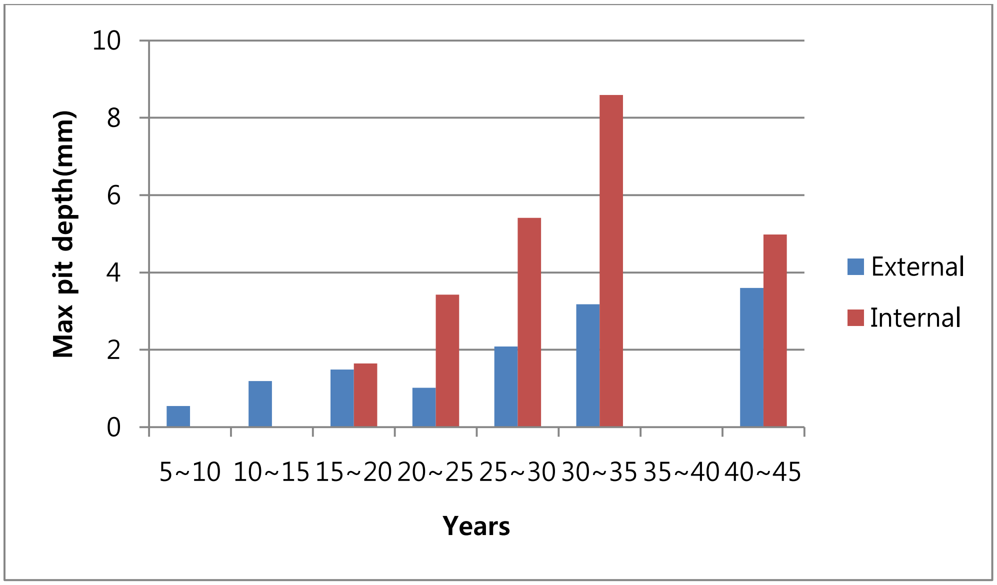


Figure 4.5 Histogram of p_{ec} and p_{ic} according to years of laying (DCIP)

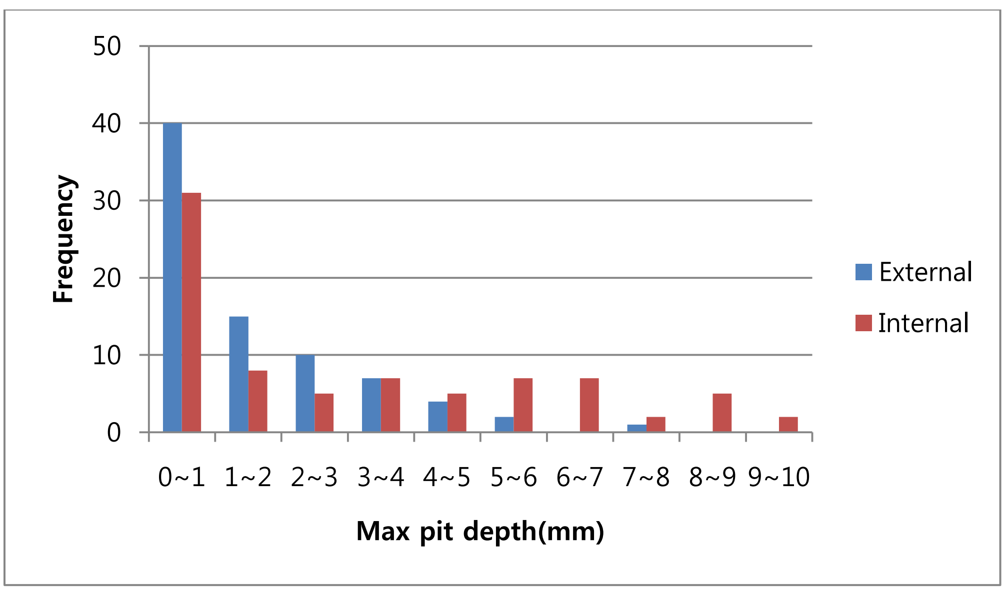


Figure 4.6 Histogram of p_{ec} and p_{ic} according to maximum pit depth (DCIP)

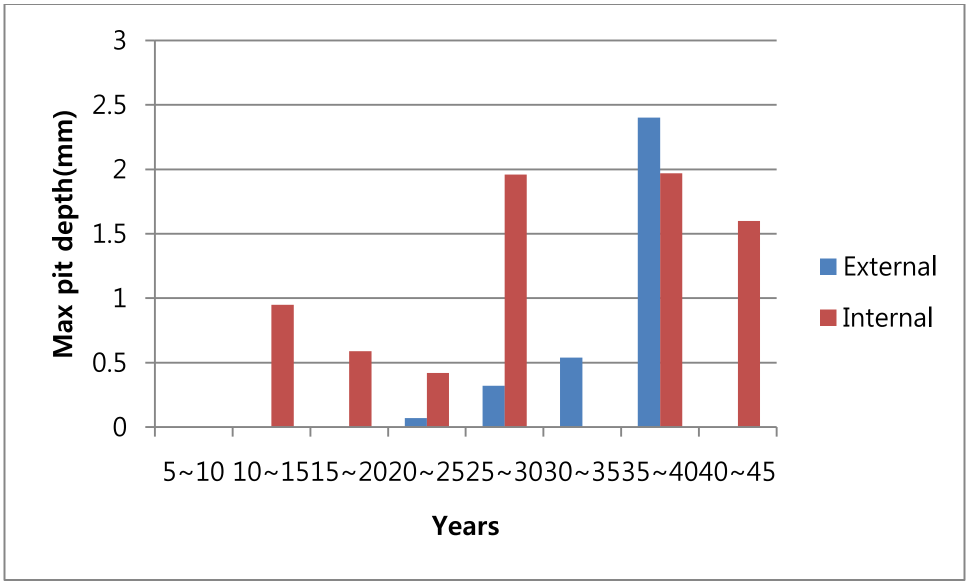


Figure 4.7 Histogram of p_{ec} and p_{ic} according to years of laying (SP)

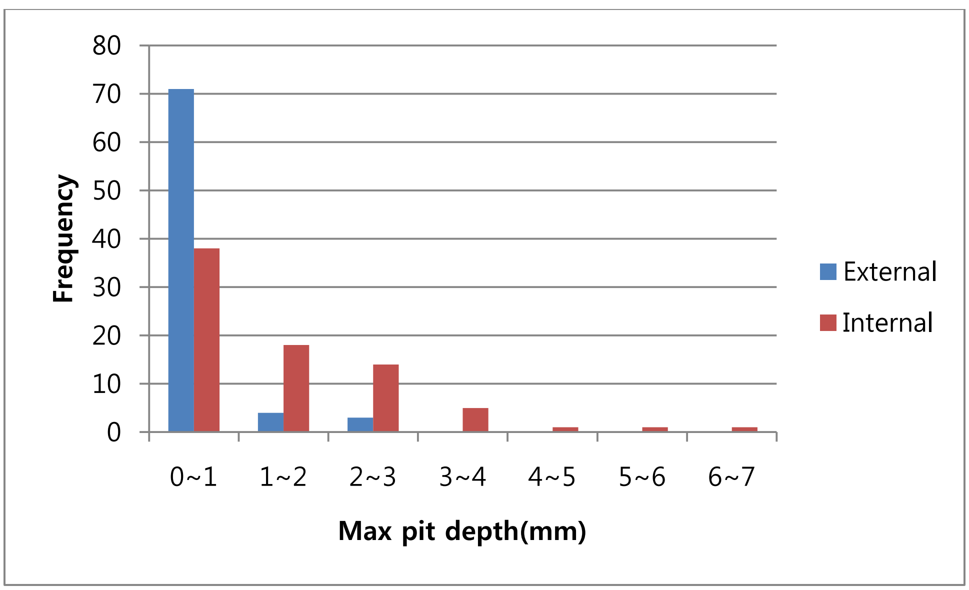


Figure 4.8 Histogram of p_{ec} and p_{ic} according to maximum pit depth (SP)

In figures 4.5 – 4.8, as buried years of both the external and internal portions increase, the depth of corrosion is increased relatively. Their corrosion depth is mostly 0 ~ 1 mm which is 51 percentage in all depths. This means that buried years of pipes strongly affected corrosion of pipes, but the corrosion depth does not.

4.3.2 Characteristics of External Pit Growth

This study simulated the growth characteristics of external pits according to years of laying by using the old experimental models (power, exponential and linear model) in order to implement a model according to the characteristics of pit growth based on years of laying. Cases of p_{ec} becoming 0 due to external coating were excluded. Since steel pipes underwent little external corrosion, they were included in the group of cast iron pipes for simulation.

Figures 4.9 and 4.10 show that the changes of p_{ec} are rather distributed instead of definitely increasing according to years of laying. Simulation results with the old experimental models reveal that the power and exponential model of the three estimated pits would yield a rapid growth due to the very rapid progress of external corrosion in the early years of laying and presented a tendency of a considerable slowdown in pit growth after ten years of laying. Since those numbers reflect the characteristics of the old mathematical models, they must reflect probability for actual phenomena.

Rajani et al. [42] multiplied the estimation value by 3 for higher growth rates than the estimation value through the corrosion depth models to obtain the maximum corrosion depth growth.

In Figures 4.9 - 4.10, the longer the pipe was buried, the more pec growth slowed down. This is because corrosion products grow according to years of laying and impose restrictions on reactions between pure metal and corrosion factors, thus affecting the rate of electrochemical corrosion mechanism. External corrosion depth was in a slow upward curve rather than a steep one in early days of installation, which is because soil has constant influences on external corrosion rather than huge ones in early days of installation.

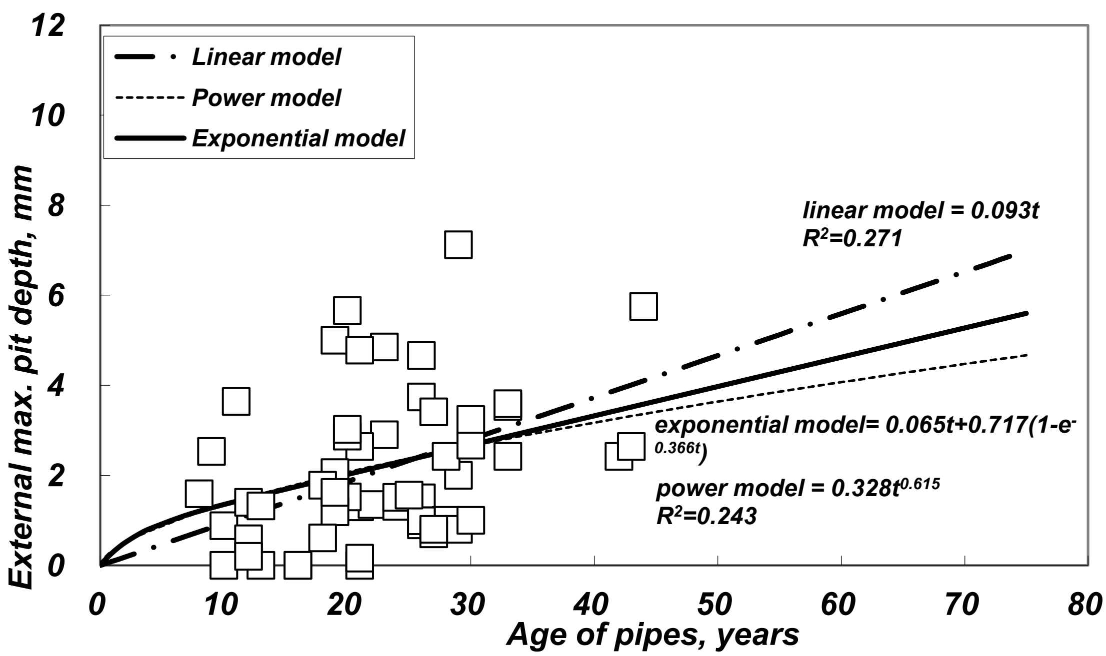


Figure 4.9 Growth rate of water pipe p_{ec} according to years of laying (DIP)

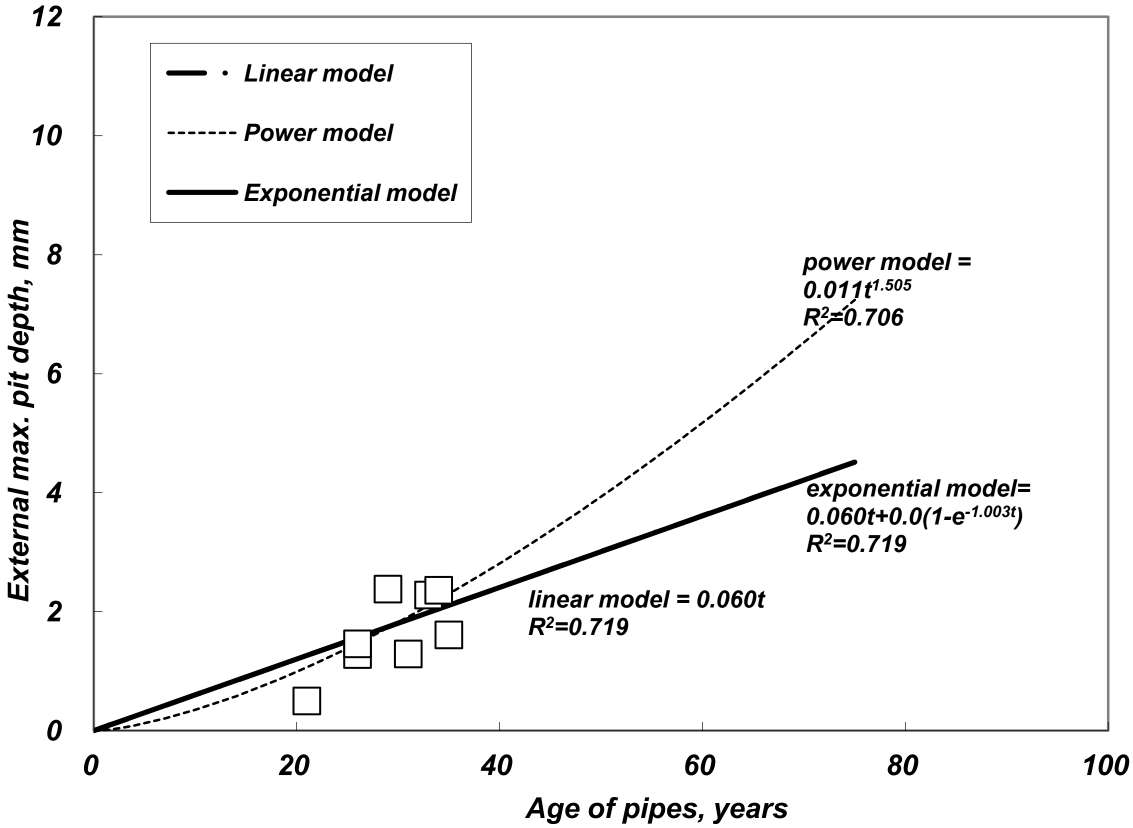


Figure 4.10 Growth rate of water pipe p_{ec} according to years of laying (SP)

In the exponential model, there was no sign of growing corrosion depth, making linear and exponential almost closer.

4.3.3 Characteristics of Internal Pit Growth

Figures 4.11 and 4.12 present the results of simulation of growth characteristics of p_{ic} according to years of laying in cast iron pipes and steel pipes by employing the method of least squares based on the experimental models. The cases of p_{ic} becoming 0 due to internal coating were excluded.

The growth characteristics of p_{ic} that depend on the years of laying of both the cast iron pipes and steel pipes are similar to those of p_{ec} in Figures 4.11 and 4.12. However, the growth rate of p_{ic} is higher than that of p_{ec} in the cast iron pipes compared to the steel pipes.

This is not because the steel pipes have a slower internal corrosion rate than the cast iron pipes, but because most steel pipes start to undergo internal corrosion only after the internal coating materials are peeled off and thus record lower internal corrosion depth than the cast iron pipes when the years of laying are the same. Thus data data reliability will not be particularly high when the steel pipe has been buried for fewer than 20 years.

As seen in Figure 4.11, p_{ic} has a higher growth rate than p_{ec} in cast iron pipes because the influential factors of internal corrosion have greater impacts on corrosion than those of external corrosion and thus p_{ic} grows faster than p_{ec}.

Table 4.1 compares each variable value of the model built based on each of the experimental models and the previous research findings.

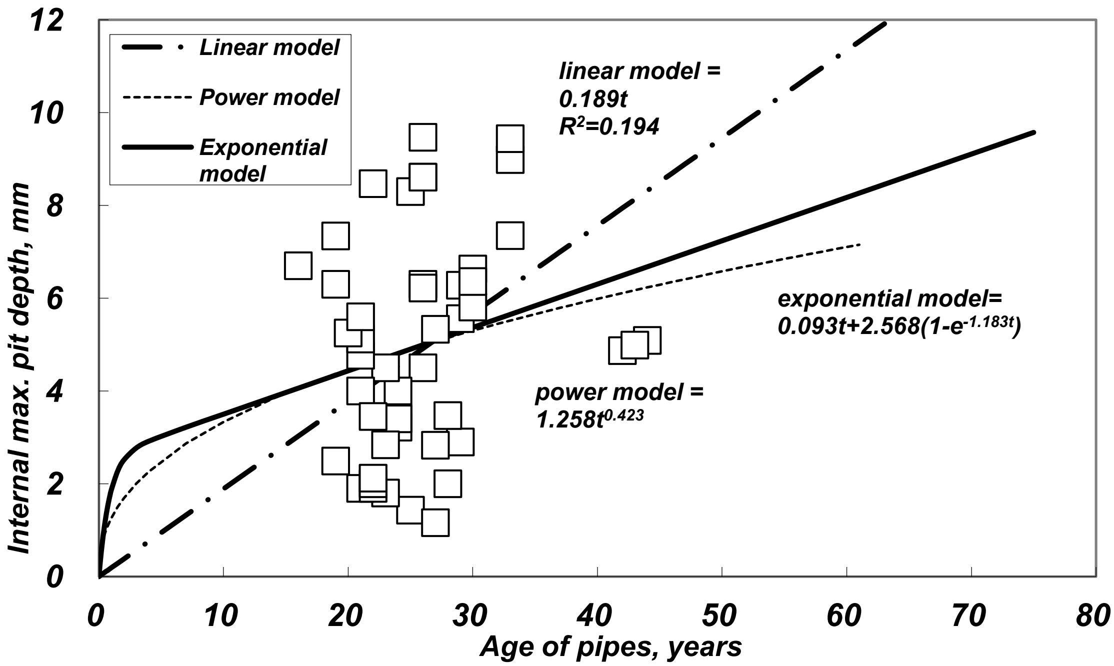


Figure 4.11 Growth rate of p_{ic} according to years of laying (DIP)

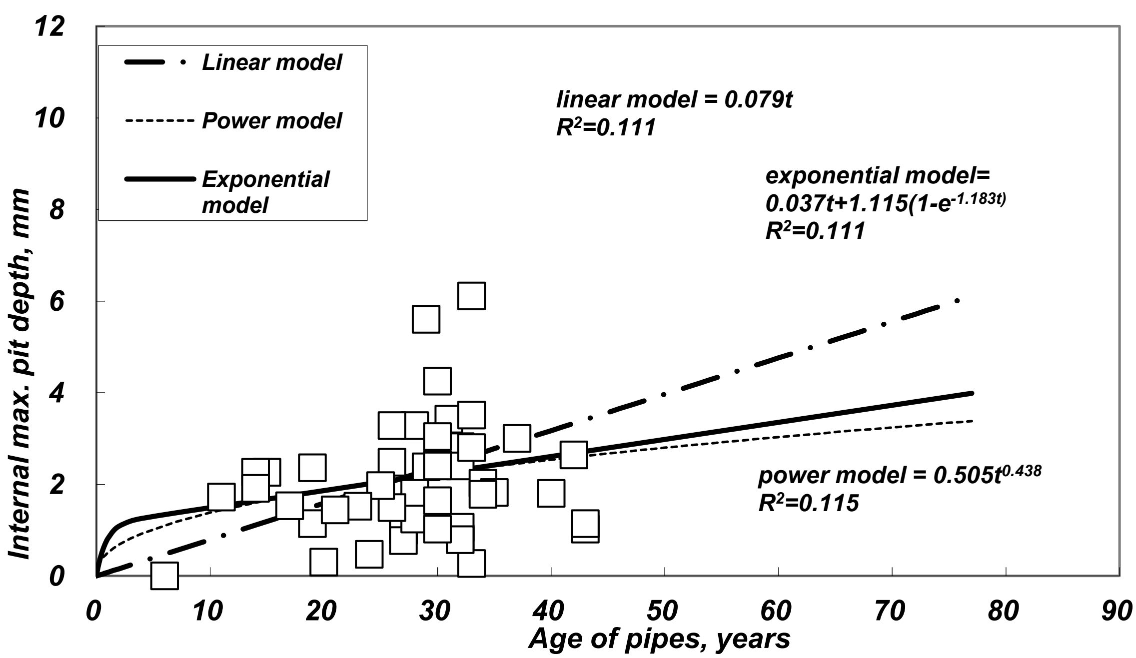


Figure 4.12 Growth rate of p_{ic} according to years of laying (SP)

Most plots in the graphs are placed in some specific range of years such as 20 to 30 ages, so the values of R square are very low. Due to this reason, many researchers have not mentioned about R square data for their study.

Table 4.1 Corrosion growth rate by experiential model

Model types			Function	Constant	This study	Previous research
DIP	Linear	p_{ec}	kT where, T = Years k = Constant	k	0.093	0.08 (Sheikh et al.,1990)
		p_{ic}		k	0.189	-
	Power	p_{ec}	kT^n where, n = Constant	k	0.328	2.0
				n	0.615	0.3
		p_{ic}		k	1.258	-
				n	0.423	-
	Exponential	p_{ec}	$aT + b(1ne^{-cT})$ where, a, b, and c are constants	a	0.065	0.0125
				b	0.717	5.85
				c	0.366	0.058 (Rajani et al,2000)
		p_{ic}		a	0.093	-
				b	2.568	-
				c	1.183	-
SP	Linear	p_{ec}	kT where, T = Years k = Constant	k	0.060	-
		p_{ic}		k	0.079	-
	Power	p_{ic}	kT^n where, n = Constant	k	0.011	
				n	1.505	
	Exponential	p_{ic}	$aT + b(1ne^{-cT})$ where, a, b, and c are constants	a	0.038	
				b	1.115	
				c	1.183	

4.3.4 Characteristics of CML Changes according to Years of Laying

Unlike common CIP, DCIP with a cement mortar lining (CML) has a zero mm of internal corrosion depth and thus is not much affected by water quality as seen in Figure 4.3 when there is no neutralization or damage to the lining. Thus it is required to assess when CML neutralization reaches 100% and triggers internal corrosion inside the pipe body in order to estimate the life of DCIP as mentioned earlier.

AWWARF [49] reported that a cement mortar lining-ductile cast iron pipe (CML-DIP) benefits from the anti-corrosive lining in the early days, but the anti-corrosive effects are eventually lost due to neutralization with the passage of time.

Thus this study assessed the neutralization rate of DCIP by CML based on the field study findings about DCIP and presents the results obtained in Korea, as shown in Figure 4.13, when it was around 1984 that CML made its full-scale debut in the field of DCIP.

In Figure 4.13, the longer the pipe is buried, the greater the neutralization degree becomes. Since the CLM neutralization degree varies widely with the same years of laying, the R^2 value is not high. In addition, the examined pipe bodies did not come from the same area but from many different areas, which means there must have been various causes, including long-term water quality and quality differences (cement combination and surface bitumen state), among manufacturers. Thus it is required to assess those influential factors as well as to make a more accurate estimation of the CML neutralization rate. In Figure 4.9, the DCIP will reach 100% of neutralization in approximately 30 years.

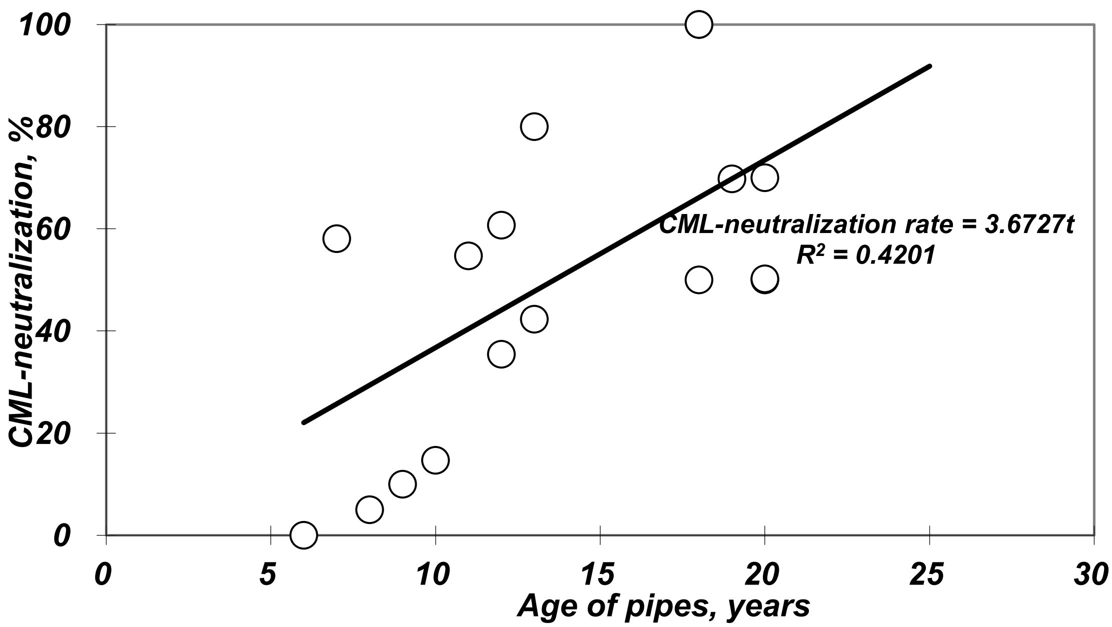


Figure 4.13 Neutralization degree of CML according to years of lying

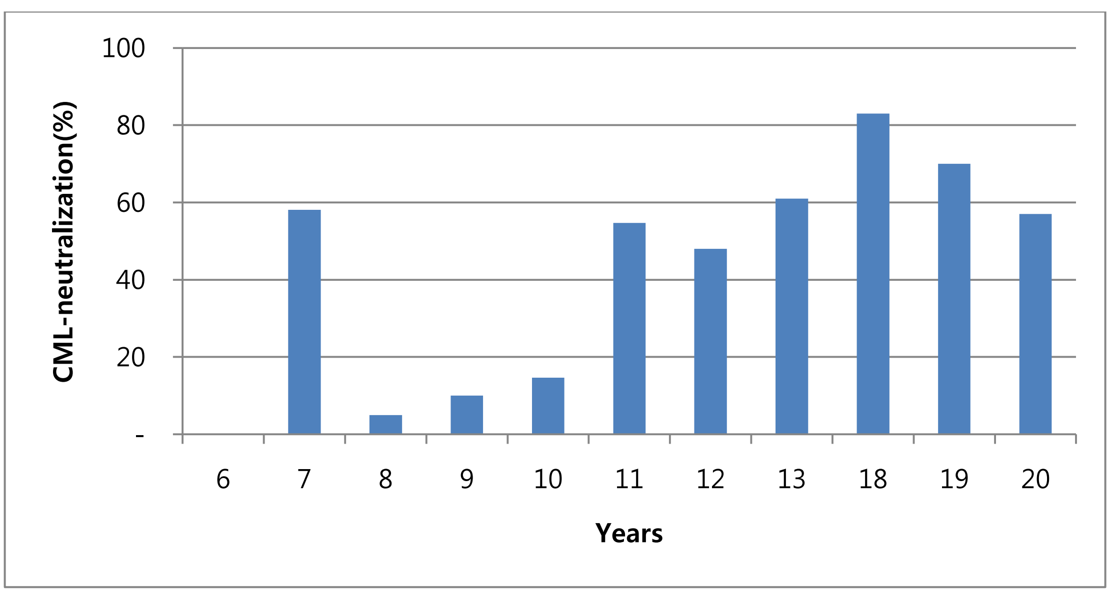


Figure 4.14 Histogram of neutralization degree of CML according to years of laying

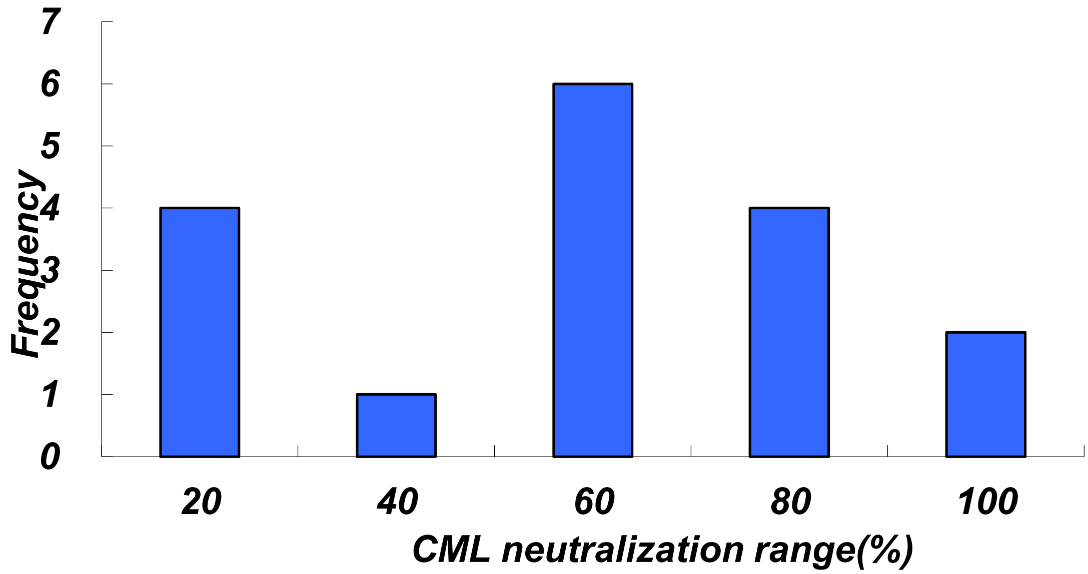


Figure 4.15 Histogram of frequency according to neutralization degree of CML

Figures 4.14 and 4.15 represent that either external coal tar enamel lining or asphalt lining does not have a relation with exfoliation of lining.

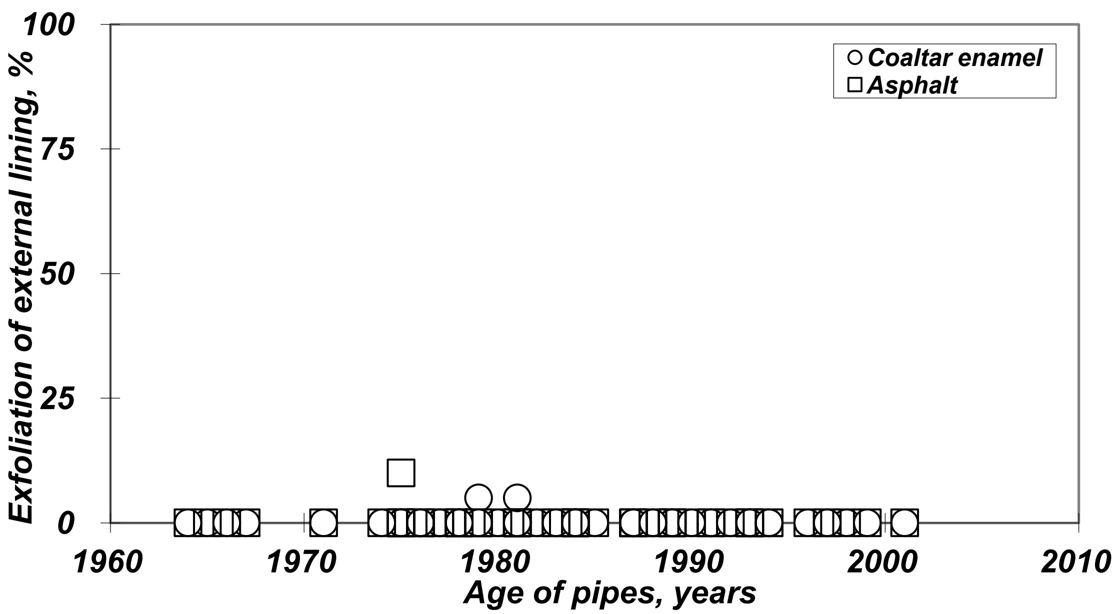
4.3.5 Characteristics of Exfoliation of Coating Materials according to Years of Laying

4.3.5.1 Exfoliation Percentage of Coating Materials

In general, water pipes have been coated with coal tar enamel and epoxy inside along with asphalt, coal tar enamel, and polyethylene outside to prevent corrosion of the pipe body. With steel pipes, nodes are formed around where internal and external coating materials are peeled off. Once the pipe bodies are corroded, they eventually fail. This study examined the steel pipes of the metropolitan water networks buried for the conditions of internal and external coating materials. Results are found in Figure 4.16, which shows that no exfoliation happened to most of the coating materials outside according to years of laying except for one location. On the other hand, the internal coating materials of steel pipes exhibited a range of exfoliation conditions from 10 to 100%. Most of the steel pipes buried before 1975 recorded a high exfoliation percentage of coating materials. Of those buried between 1975 and 1990, 43% underwent no exfoliation of coating materials, and about 57% were in progress of exfoliation in coating materials. The average exfoliation percentage of coating materials of steel pipes was about 50%.

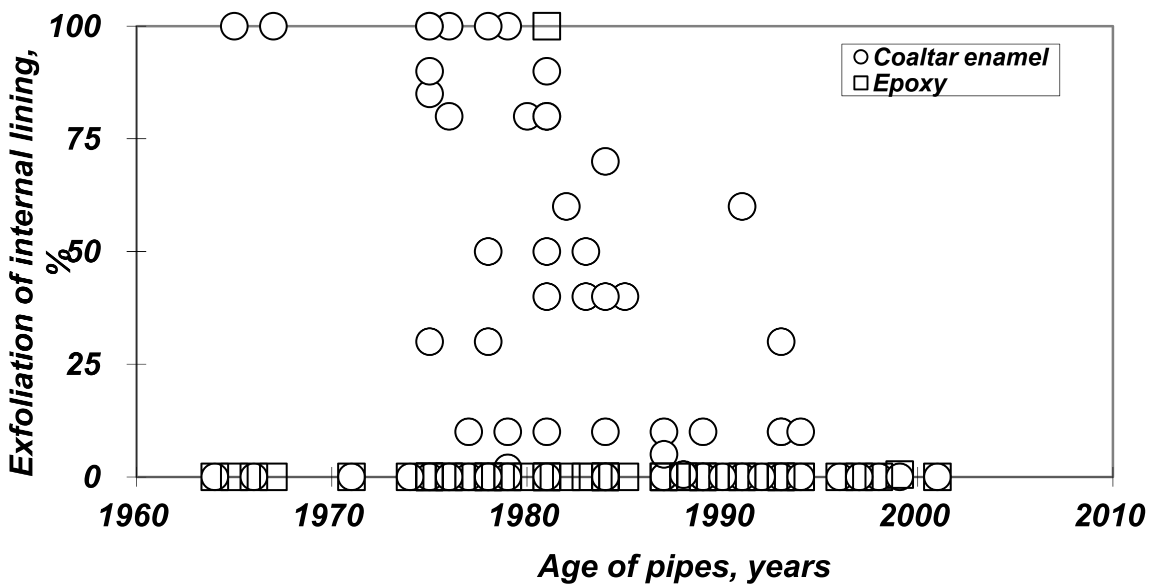
Figure 4.16 shows changes in the exfoliation of coating materials in the steel pipes according to years of laying. In the figure, the burial years of the steel pipes with no coating materials peeled off spanned from 9 to 28 years. Their average years of laying was 18 years. The steel pipes in progress of coating material exfoliation were buried from 12 to 40 years with an average of 26 years. Changes to the exfoliation of coating materials in all the steel pipes in the figure were estimated. Results showed that the coating materials started to peel off after 13 years of laying and reached the full exfoliation stage after about 35 years of laying. However, more than 43% of the examined steel pipes experienced no exfoliation of coating materials, which raises a need to make various investigations on the causes of coating material exfoliation in steel pipes in order to produce more accurate results and build a more reliable model. So far such causes as quality differences (coating materials and adhesive strength of coating materials) in steel pipes among manufacturers, differences in the coefficient of linear expansion over a long period of time, and construction errors (excessive variation) have been identified. However, it is realistically difficult to examine those causes closely at this point.

This study assessed the impact of excessive variation in exfoliation in certain sections. In Figure 4.16, which shows the connection between the exfoliation percentage of coating materials and the variation rate at five points in the SD-II section; there was an excessive variation, which led to exfoliation and relatively higher percentage of exfoliation, even though the years of laying was 27 years. Once additional data about the connection between the variation rate and the exfoliation of coating materials in steel pipes are obtained, the exfoliation of coating materials can be estimated.



(a) outside

Figure 4.16 Exfoliation percentage of coating type according to years of laying



(b) inside

Figure 4.16 Continued

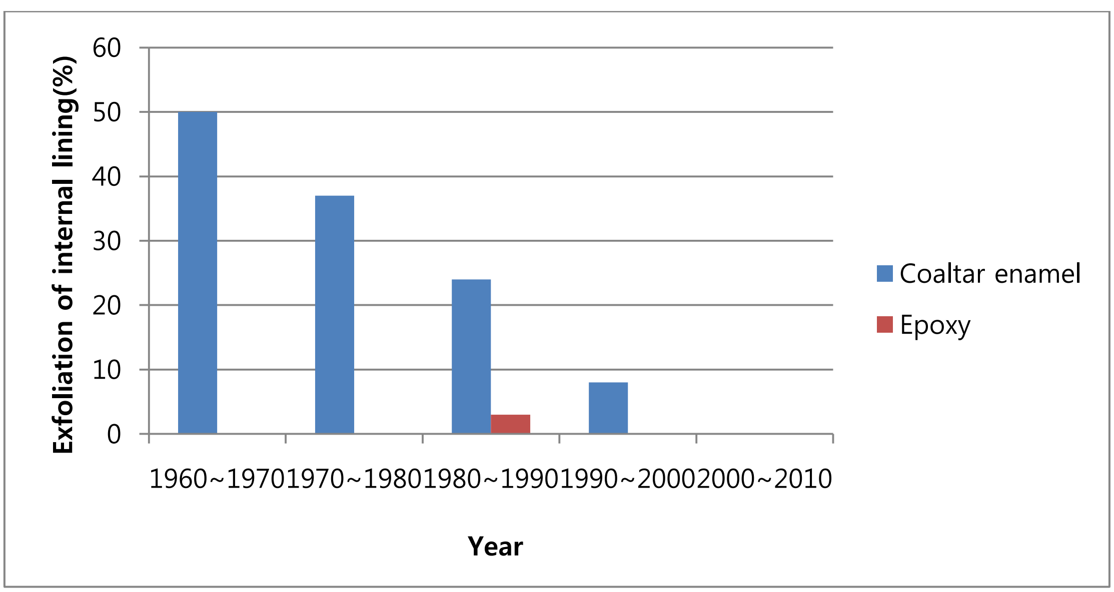


Figure 4.17 Histogram of exfoliation percentage of lining according to years of lying

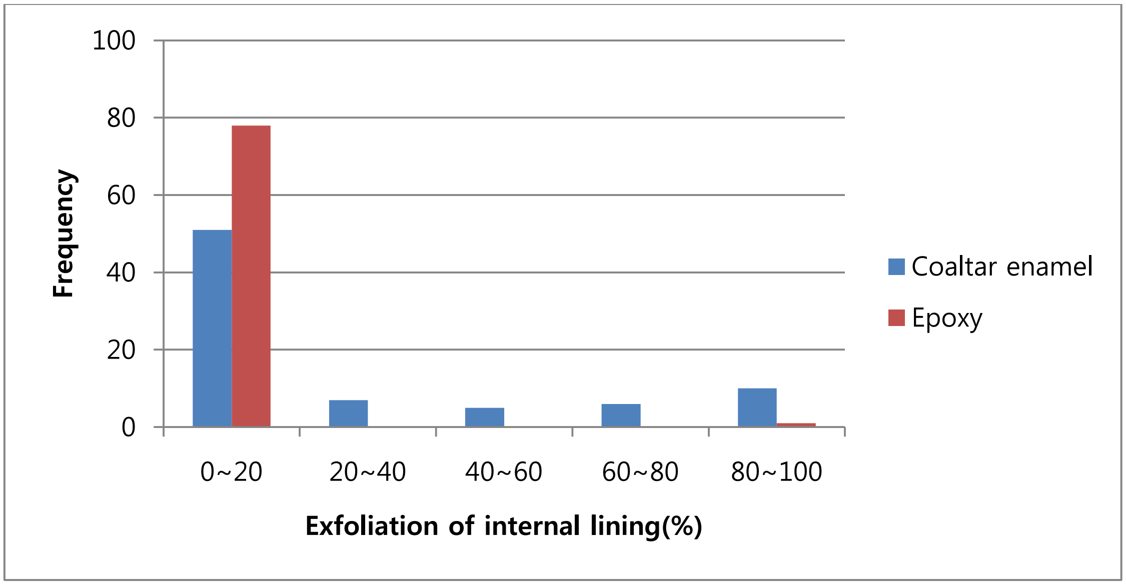


Figure 4.18 Histogram of frequency according to exfoliation percentage of lining

Figures 4.17 and 4.18 show that old pipes in buried years have a large value of exfoliation of lining, but epoxy lining is not related to exfoliation of lining. Most invested pipes have a good exfoliation of lining condition

4.3.6 Changes in EIS Characteristics of Coating Materials in Steel Pipes according to Years of Laying

Currently available methods to assess the life expectancy of a pipe employ a set of economic value criteria through legally prescribed useful life, physical failure risk, or break-even point. Good examples of these methods are the deterioration point assignment method, break-even analysis method, stochastic analysis method such as a survival function using statistical techniques, and physical estimation model.

Of them, the physical model delivers different failure mechanisms and requires different models for different pipe materials. In particular, estimation for coating materials should precede estimation for the failure risk of the pipe body and the entire life and residual life of the pipe when it is a steel pipe, whose body starts to corrode only after the internal and external coating materials reach the end of life.

Since coating materials themselves are the means to protect the body of a steel pipe from corrosion, anti-corrosive performance is most important. This study thus investigated changes in the anti-corrosive performance of a steel pipe or EIS (Electro-impedance spectroscopy) according to years of laying and compared the results with the old results about exfoliation states observed with the naked eye.

4.3.6.1 EIS Measurement

This study measured EIS for internal and external coating materials and adhesive strength for the inside in order to assess the life of coating materials and examined the exfoliation of coating materials in the sections where EIS and adhesive strength were measured with the naked eye.

4.3.6.1.1 Overview of Electro-Impedance Spectroscopy (EIS) Measurement

EIS is a performance indicator for various types of organic polymer lining. An EIS point of 8 or higher means great anti-corrosive performance; an EIS point of 6 or higher means the presence of anti-corrosive performance; and an EIS point of 4 or lower means loss of anti-corrosive performance. In the study, EIS was measured for internal and external coating materials of steel pipes as a means of assessing their life. Figure 4.19 shows that criteria of anti-corrosive performance of coating according to EIS values.

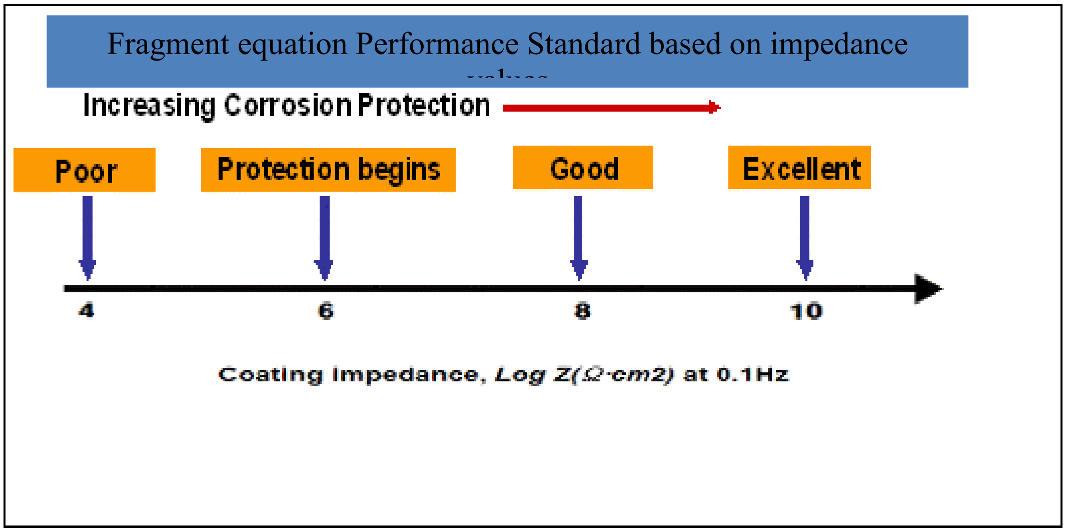


Figure 4.19 Criteria of anti-corrosive performance of coating according to EIS values

4.3.6.1.2 Principles of EIS Measurement

Coating materials are a means of protecting the body of a steel pipe from corrosion. Corrosion progresses by an electrochemical mechanism, and coating materials with insulation functionality cut off the flow of corrosion currents to the pipe body and thus prevent corrosion. While having insulation functionality, however, coating materials deteriorate with time. Electrolytes and moisture penetrate and eventually lead to corrosion in the pipe body. Once moist, penetration occurs, coating materials peel off from the pipe surface. Nodes are formed on the surface of the pipe body, and corrosion occurs in the pipe body itself. The end result is a hole or rupture.

EIS measures whether coating materials have resistance against current flows when exposed to electrolytes. For EIS measurement, a container containing electrolytes is attached to the surface of coating materials, electrochemical cells are made through the ground of a wire to the pipe body, and the resistance due to EIS of coating film is measured. Figure 4.20 shows that principles of EIS measurement.

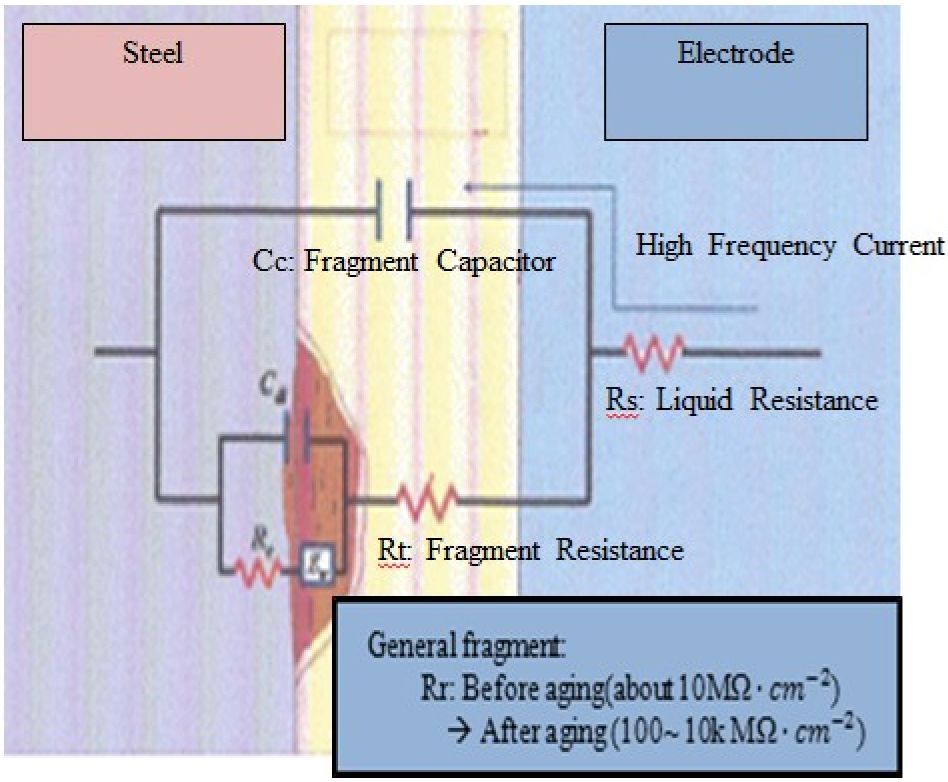


Figure 4.20 Principles of EIS measurement

4.3.6.1.3 Device Composition

The EIS measuring device consists of a potentiostat with FRA, SP-150 standard electrode, reference electrode (Pt), 3-terminal cell cable, and load cell (electrode for liberation testing). This study used the EIS EC-150 model. Figure 4.21 shows that EIS device composition

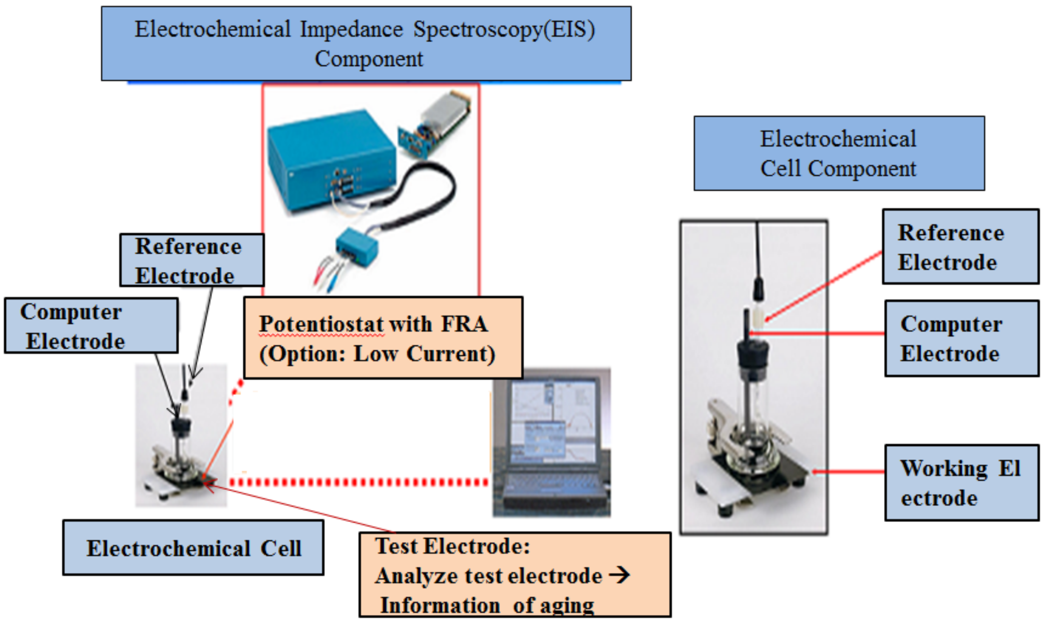


Figure 4.21 EIS device composition

4.3.6.2 EIS Measurements according to Years of Laying

The EIS of coal tar enamel gradually decreases according to years of laying, dropping to 6 Log Z(Ω.cm^2) or lower in 25 to 30 years of laying. Linda et al. [64] reported that anti-corrosive performance started at EIS 6 Log Z(Ω.cm^2) or higher. Coal tar enamel is estimated to drop to 6 or lower in 25 years of laying due to deterioration and thus highly likely to affect internal corrosion.

Figures 4.22 and 4.23 show changes in the exfoliation percentage and EIS in the internal and external coating materials of steel pipes according to years of laying through field study. In Figure 4.22, coal tar enamel, an internal coating material, undergoes partial exfoliation within 10% in 10 to 15 years of laying and 30~100% of exfoliation in 20 to 30 years of laying to lose its functions as a coating material. There was no case of a water pipe whose exfoliation percentage was 0% after 25 years of laying. In Figure 4.22, EIS is in the range of 6~7 Log Z ($\Omega . cm^2$) when the exfoliation percentage of coating materials rises quickly. The anti-corrosive performance of an internal coating material seems to be lost in its entirety after 25 years of laying or more.

In Figure 4.23, the EIS of an external coating material drops to 6 Log Z ($\Omega . cm^2$) or lower after 30 years of laying, but no actual exfoliation happens. Exfoliation is attributed to welding or other construction defects rather than natural deterioration in most cases. The absence of exfoliation is also attributed to the fact that soil is firmly attached to the outer wall of the pipe and thus prevents an external coating material from moving to another location unlike an internal coating material in spite of deterioration. When there is no external construction damage or source of damage in case of re-filling, an external coating material will last for at least 40 years.

In addition, it is required to adjust the EIS of an external coating material to 6 Log Z($\Omega . cm^2$) or lower unlike an internal coating material.

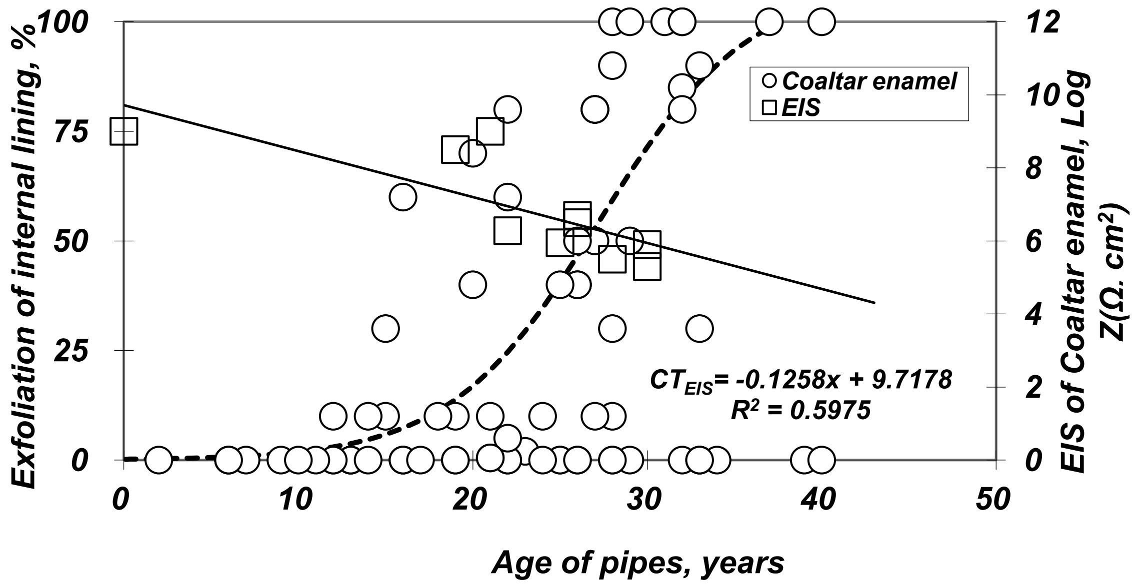


Figure 4.22 Relations between exfoliation percentage and EIS in internal coating materials

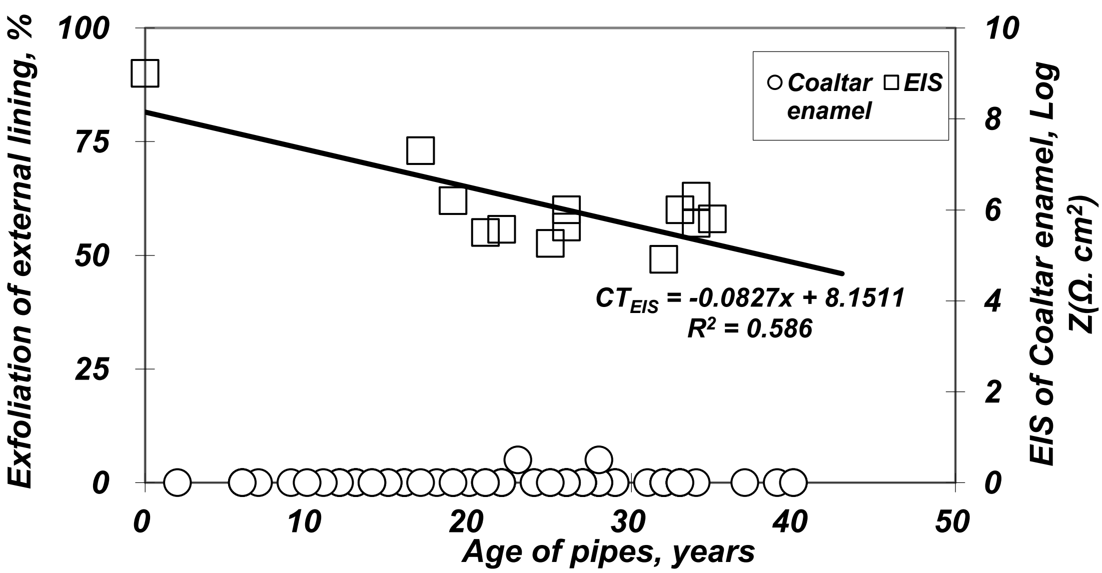


Figure 4.23 Relations between exfoliation percentage and EIS in external coating materials

4.3.6.3 Life of Coating Materials

This study measured the anti-corrosive performance of coating materials according to years of laying through EIS to figure out the life of coating materials and further steel pipes and compared the findings with the exfoliation states of the old coating materials. The following was observed:

First, coal tar enamel usually used as an internal coating material dropped to EIS 6 Log Z($\Omega . cm^2$), the old recommended limit, or lower after about 25 years. Some of the old internal coating materials reached 30~100% of exfoliation in 20 to 30 years. There was no section with no exfoliation in the pipes examined in the study after 25 years. Thus the life of internal coating materials seemed to be at least 20 years.

Second, coal tar enamel as an external coating material tended to drop to EIS Log Z ($\Omega . cm^2$) or lower after 25 years. There was almost no exfoliation unless there was a construction error after laying. Asphalt maintained its EIS 6 Log Z ($\Omega . cm^2$) or higher after 35 years of laying. Thus the life of external coating materials seemed to be 10 to 20 years longer than that of internal coating materials.

Third, given the tendency of exfoliation percentage among the old internal and external coating materials, the standard of EIS anti-corrosive performance should be 7 or lower for internal coating materials and 5 or lower for external ones.

4.4 Model for Estimation of Residual Strength

Corrosion occurs in the pipe body in a very irregular way. The corroded section contains corrosion products, such as black lead, on the surface. Thus it is extremely difficult to cut a section of the pipe body that is most affected by corrosion for mechanical testing. Therefore, a researcher should collect a group of samples with various corrosion characteristics from the pipe body, assess the influence according to corrosion percentage, and evaluate the current safety factor by estimating residual strength based on the maximum corrosion percentage.

This study collected samples from the metropolitan and local water pipes across the nation in order to develop a model for estimation of the residual strength of metal water pipes, as well as a measured (based on the tensile testing standard) total of 125 samples (34 from CIP, 68 from DIP, and 23 from SP) for residual strength according to pit characteristics, as plotted Figure 4.24. In the figure, tensile strength is an indicator of the strength that the pipe can endure of stress caused by pipe rupture or longitudinal stress. Circumferential bending fracture strength is an indicator of the strength that the pipe can endure of hoop stress against external load. Longitudinal bending fracture strength is an indicator of the strength that the pipe can endure of longitudinal stress caused by the unstable foundation of the pipe.

When it was a pure metal with no corrosion in Figure 4.24, the residual tensile strength of CIP was an average 2,031 kgf/cm^2, that of DIP was 4,096 kgf/cm^2, and that of SP was 4,579 kgf/cm^2. Once corrosion progressed in the pipe body, the strength decreased in a linear fashion. Since steel pipes were usually used as large-diameter pipes, it was difficult to collect SP samples in the field. Given that SP samples were gathered at only two locations, it was necessary to gather additional data. Table 4.2 shows prediction model of residual strength according to corrosion rate.

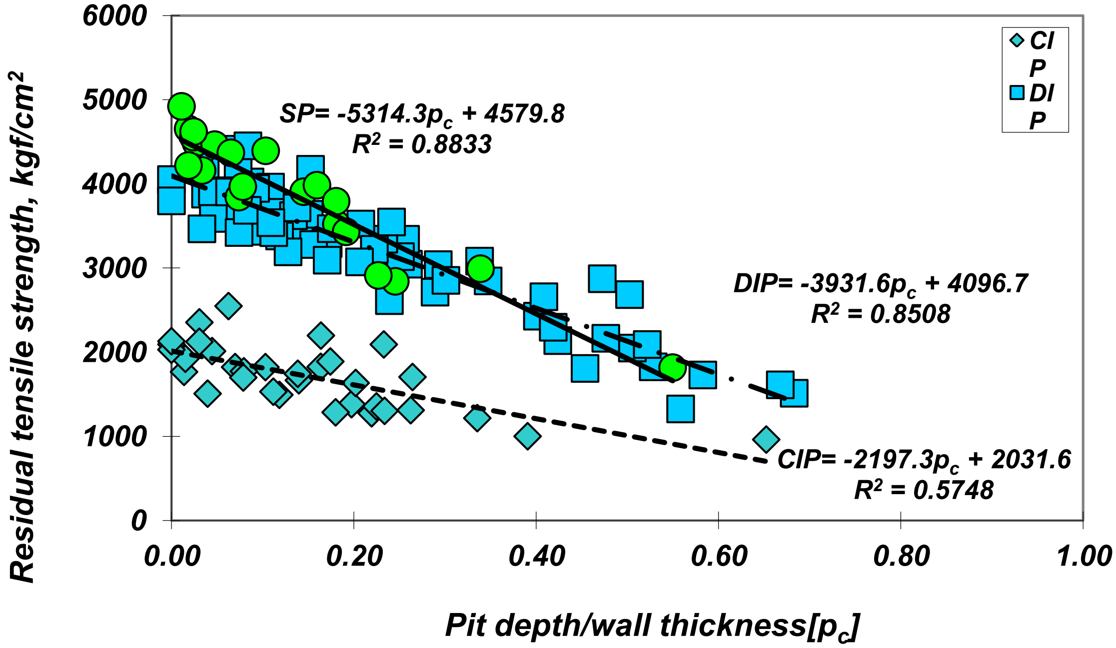


Figure 4.24 Change of residual tensile strength according to corrosion rate

Table 4.2 Prediction model of residual strength according to corrosion rate

Model types	Functions	Constant	Pipe materials		
			CIP	DIP	SP
Residual tensile strength	$\sigma_{res} = a * p_c + b$ where, σ_{res} = Residual tensile strength, kg_f/cm^2 a, b= Constant	a	-2,197.3	-3931.6	-5314.3
		b	2031.6	4096.7	4579.8

4.5 Conclusion

In this study, the investigator collected the bodies of cast iron pipes and steel pipes, which were part of the metal pipe types used in water pipes, at a total of 178 points, measured them in internal and external corrosion depth, CML neutralization, exfoliation of coating materials, and residual strength, and proposed a model to predict physical damage risk. The findings were as follows:

First, the measurements of internal and external corrosion depth show that the external maximum corrosion depth (p_{ec}) of cast iron pipes was 1.64mm, which was 1.87 times smaller than 3.07mm of the internal maximum corrosion depth (p_{ic}). The difference can be attributed to the fact that water quality, one of the influencers of internal corrosion, has more corrosive impact on the deterioration of metal water pipes than soil, one of the influencers of external corrosion in Korea. The ductile cast iron pipes lined with cement mortar were not affected by corrosion in most cases thanks to the anti-corrosive effects of cement mortar and were more subject to deterioration caused by external corrosion. The steel pipes, which were coated both in and outside, showed more corrosive damage inside than outside due to the early exfoliation of coal tar enamel, which was used as an internal coating material.

Secondly, a power, exponential, and linear model were built to predict the growth of corrosion depth based on the measurements of internal and external corrosion depth. As a result, the exponential model showed that there was a very rapid growth in the growth of internal and external pit in the cast iron pipes in the initial stage and that the growth rate started to slow down after the initial stage. It seems to reflect an assumption that corrosion products will be form on the in- and outside surfaces in the initial stage of installation and that those products prevent a contact between the pipes and water or soil, thus slowing down the corrosion rate. It was predicted that the corrosion depth would grow to about 2mm inside and 5mm outside on average for the first 50 years of installation. Those predictions can be bigger according to the soil or water environments of the areas where the pipes are buried, considering the deviations in corrosion depth among the collected pipe bodies. In a linear model that took no considerations of the influence of corrosion products, the growth rate of internal pit was estimated at 0.189mm/yr., which was over two times higher than 0.093mm/yr. of external pit.

The internal corrosion depth or corrosion rate of steel pipes is usually affected by the exfoliation of internal coating materials, which explains why there was no big difference found among the power, exponential, and linear model.

Thirdly, there were huge deviations in the neutralization of cement mortar lining (CML) in cast iron pipes according to the water quality characteristics of the areas where the pipes were buried. It was estimated that neutralization would reach 100% after 30 years of burial on average.

The external coating materials of steel pipes could last for 40 years or longer when there is no damage on the surface during construction or re-filling. Coal tar enamel drops to 6 Log Z(Ω.cm2) or lower in EIS after 25 years, which means that the pipes coated with it will be highly likely to be affected by corrosion after 25 years even though there is no exfoliation of the coating material.

With internal coating materials, exfoliation starts to rise rapidly once past the 13-year milestone. Their exfoliation is usually caused by water penetration, weakening adhesion between coating materials and the metal surface, difference in coefficient of linear expansion between metal and coal tar enamel, and deterioration of coal tar enamel itself. The EIS of coal tar enamel drops to the recommended level of 6 Log Z (Ω . cm2) or lower after about 25 years, which means that coal tar enamel would lose its anti-corrosive efficacy after 25 years even though it is still partially attached to the inside surface of the pipe. In short, the expected life of coal tar enamel, an internal coating material, seems to be 13 years according to the exfoliation criteria and 25 years according to the EIS criteria.

Finally, the residual tensile strength of the pipes was also measured according to the geometric characteristics of their pits. There were differences in the strength of pure metal according to different manufacturers of different quality levels even though the corrosion depth was the same. The pure metal strength of CIP, DIP, and SP was 2,031.6 kgf/cm2, 4,096.7 kgf/cm2, and 4,579.8 kgf/cm2, respectively. As corrosion depth grew, residual strength tended to drop in a linear fashion.

5. APPLICATION OF AN ESTIMATION MODEL FOR FAILURE RISK

This section estimated load, residual strength and SF of water pipes and then determined a method and time of rehabilitation based on estimation criteria of pipe condition for rehabilitation.

5.1 Survey of Water Pipes in the Area

The study reviewed the applicability of the deterioration point assignment method to assess pipe life in the Changwon, South Korea, area with a metropolitan water network in the nation. The water network of the Changwon, South Korea, area extends a length of 75,443 ㎞, 69.8% (52,651 ㎞) of which was installed before 1990. The water network consisted of DIP, DCIP, and SP. DIP accounting for 43.29% of the entire water pipes in the network, extending 32.67 km. There have been civil appeals piled against the DIPs due to black and red water, lower water pressure, and foreign substances caused by the accumulation of internal scale. Rehabilitation projects have thus been implemented since 1999, renovating and replacing 29.2 ㎞ (38.7%) until 2007.

5.2 Subject Water Pipes

The subject water pipes of the study were the water transportation pipes in the Changwon, South Korea,water network. Figure 5.1 presents a diagram of the subject water pipes. Figure 5.2 shows the subject water pipes in the Chang Won City water network according to the types of pipe, pipe diameter, and years of laying. The entire length of the subject water pipes was 66.23km. DIPs extended 32.67km, and DCIPs 33.62km. The years of the subject water pipes widely varied from 4 to 35.

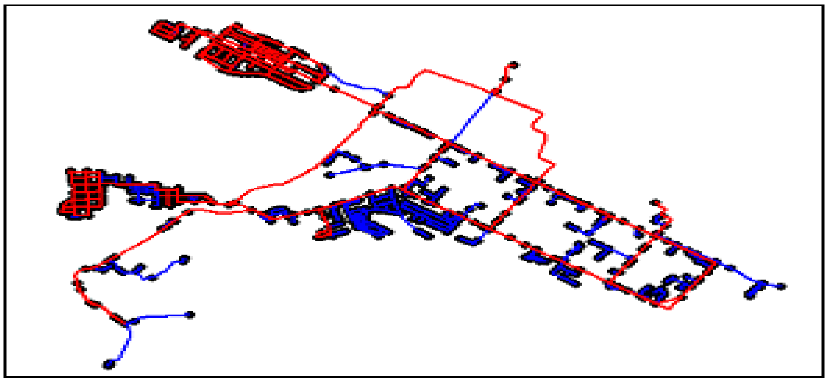
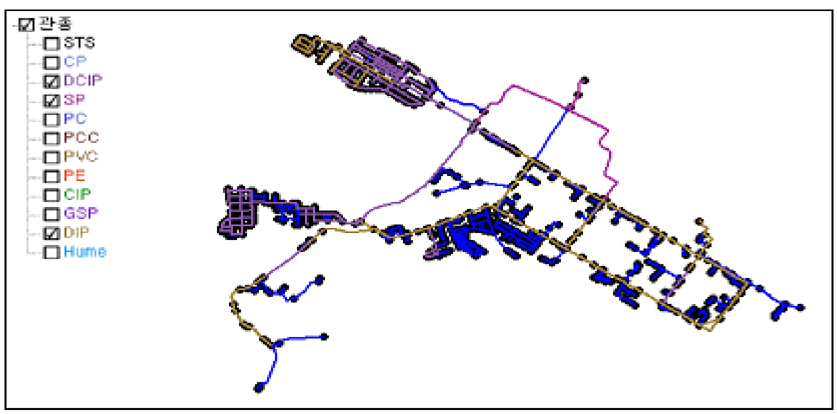
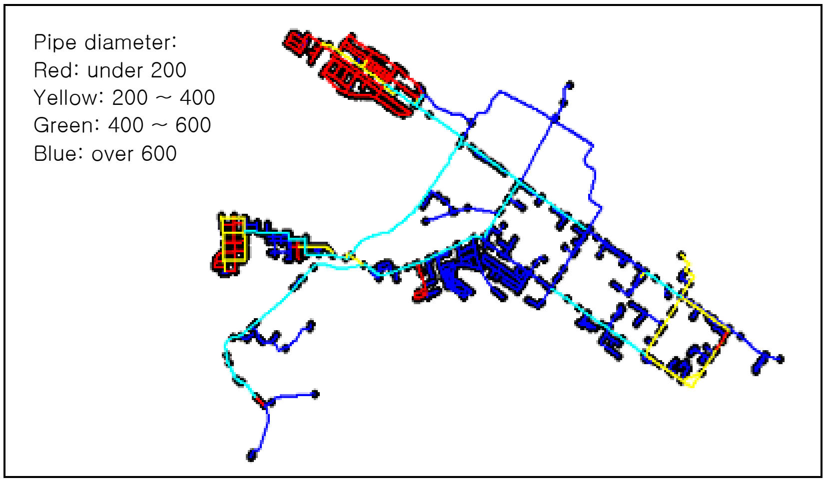


Figure 5.1 The subject water pipes in the CW area (red line)

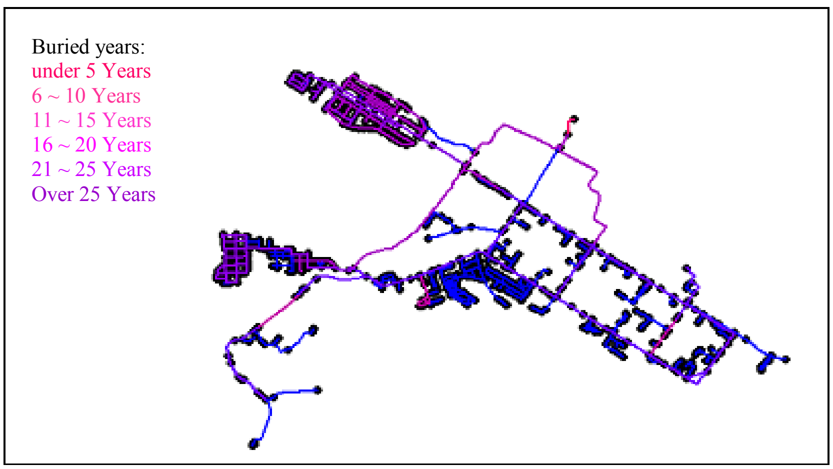


(a) Types of pipe

Figure 5.2 Survey of the subject water pipes in the Changwon, South Korea,water network according to the types of pipe, pipe diameter, and years of laying



(b) Pipe diameter



(c) Years of laying

Figure 5.2 Continued

5.3 Results of Estimation of Physical Failure Risk

5.3.1 Internal and External Load

Figures 5.3 and 5.4 show the results of calculated internal and external load in the water pipes of the Changwon, South Korea, area. Earth pressure was obtained by using the average burial depth for each section across a total of 718 sections. The truck load was obtained with the scattering angles method. The rear wheel load was 9,600 kg for all sections. The number of trucks was set at two only when it was a four-lane road.

Since it was difficult to obtain working pressure for each section, the maximum average water pressure of the entire water network was obtained by using the data collected from the pressure devices installed across the water network. The surge pressure was obtained with eq. 3.21

External load was in the range of 0.4~0.6 kgf/cm^2 in most cases and internal water pressure was in the range of 10~12kgf/cm^2, as shown in Figure 5.3 and 5.4.

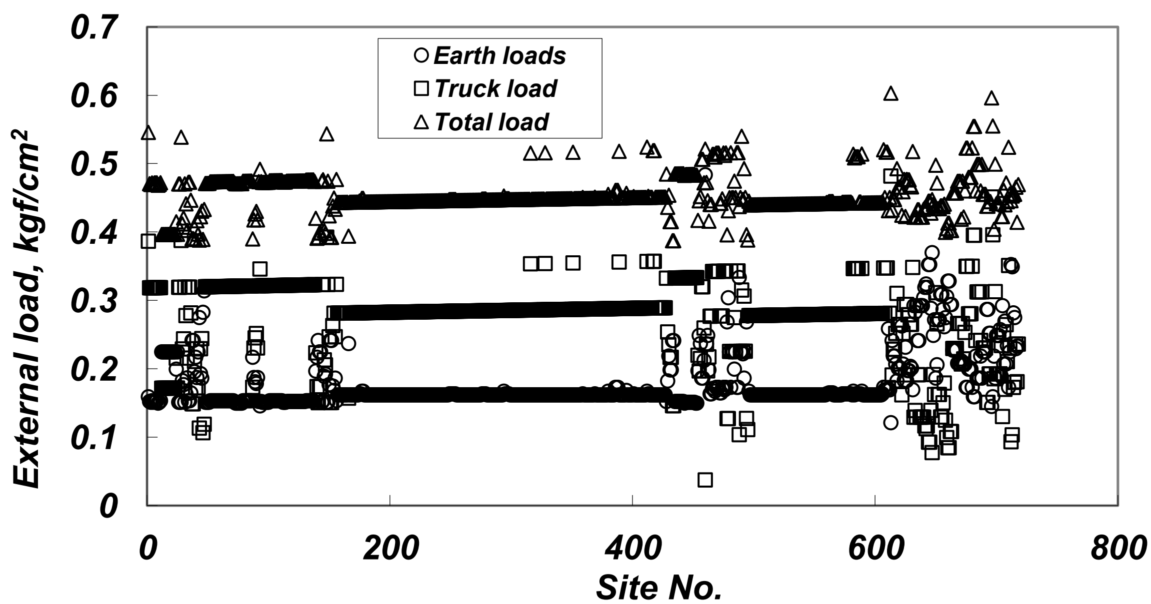


Figure 5.3 External load of water pipes in the Changwon area

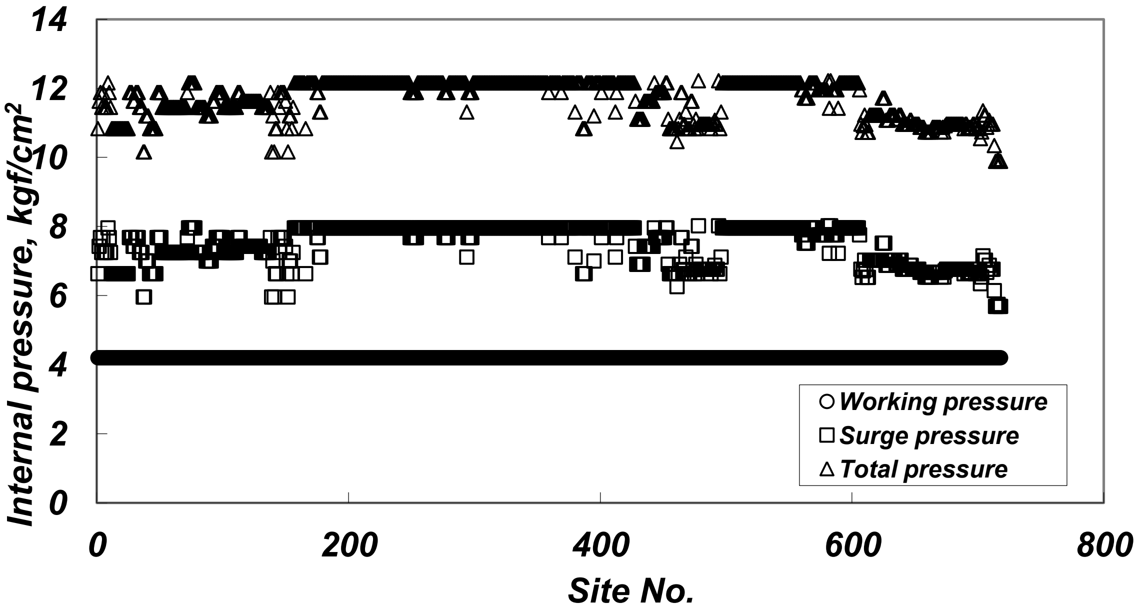


Figure 5.4 Internal pressure of water pipes in the Changwon area

5.3.2 Estimation of Corrosion Percentage according to Years of Laying

Figure 5.5 presents corrosion percentage in the Changwon, South Korea,area according to years of laying. In general, corrosion makes irregular growth in and outside. This study assumed that maximum internal and external corrosion depth would grow at the same locations by considering the safety aspects of water pipes and obtained corrosion percentage by dividing the addition of maximum internal and external corrosion depths estimated with the initial thickness by the initial thickness. Internal and external corrosion depth was obtained by using the linear and exponential model in the category of experiential models in Figure 5.5, which shows that there is no significant difference in the corrosion percentages estimated through the linear and exponential models.

In Figure 5.5, the internal CML neutralization of ductile cast iron pipes, which accounted for a majority of 25-year-old pipes or older pipes, did not yet reach 100%. With no internal corrosion in progress, corrosion percentage was relatively low. DIPs with no CML buried over 25 years recorded high corrosion percentage with the impact of internal and external corrosion taken into account at the same time. In addition, there were some differences in corrosion percentage according to the initial thickness (nominal pipe thickness) even though pipes were the same in terms of type and years of laying.

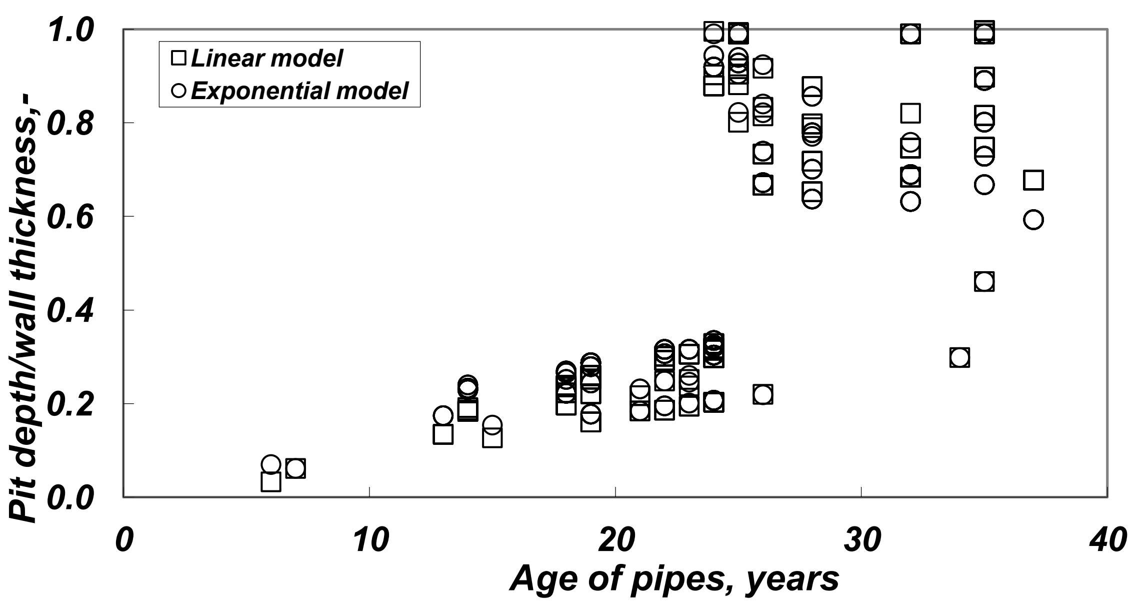


Figure 5.5 Estimation of corrosion percentage of water pipes in the Changwon, South Korea, area according to years of laying

5.3.3 Estimation of Residual Strength according to Corrosion Percentage

Figure 5.6 shows the residual tensile strength of the pipe body according to the estimated corrosion percentage. The residual tensile strength tended to decrease in a linear fashion as the corrosion percentage increased.

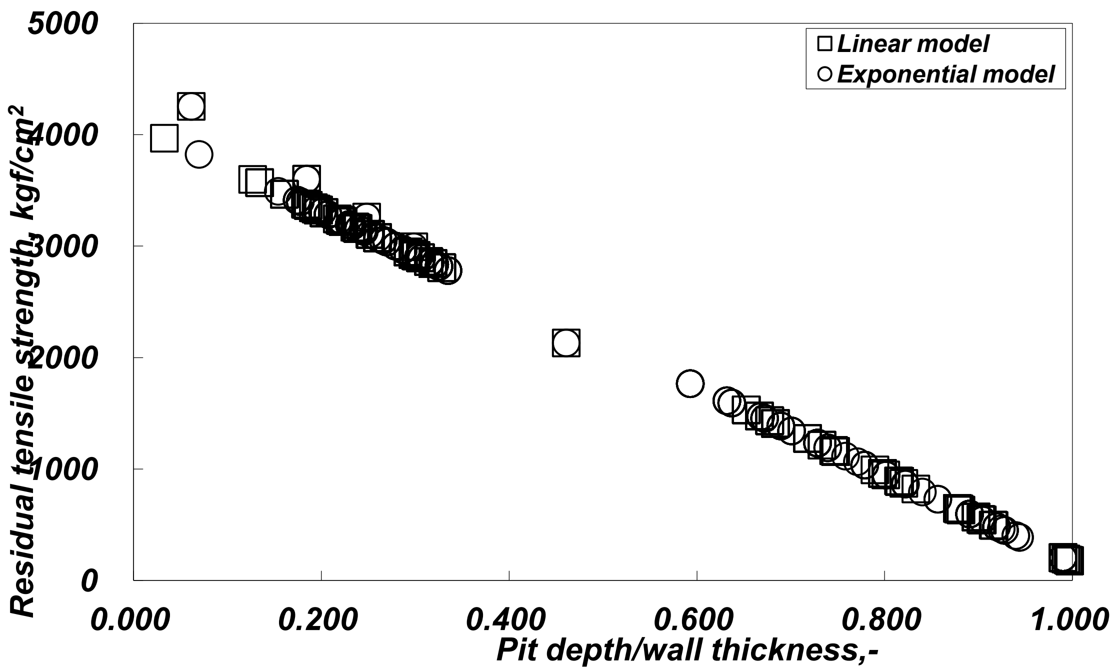


Figure 5.6 Estimation results of residual tensile strength according to corrosion percentage of water pipes in the Changwon area

5.3.4 Estimation Results of Stress

Figures 5.7-5.9 show the results of estimated stress according to the corrosion percentage of water pipes in the Changwon, South Korea, area. In general, stress on the pipe body increases with the same load as pipe thickness decreases. Figures 5.7 -5.9, thus, exhibit a tendency of increasing stress in the pipes with a higher corrosion percentage. As corrosion percentages increased, there was rapid growth in the non-linear function. Once the corrosion percentage reached a certain limit, the safety of water pipes would rapidly drop due to the decreasing thickness caused by corrosion.

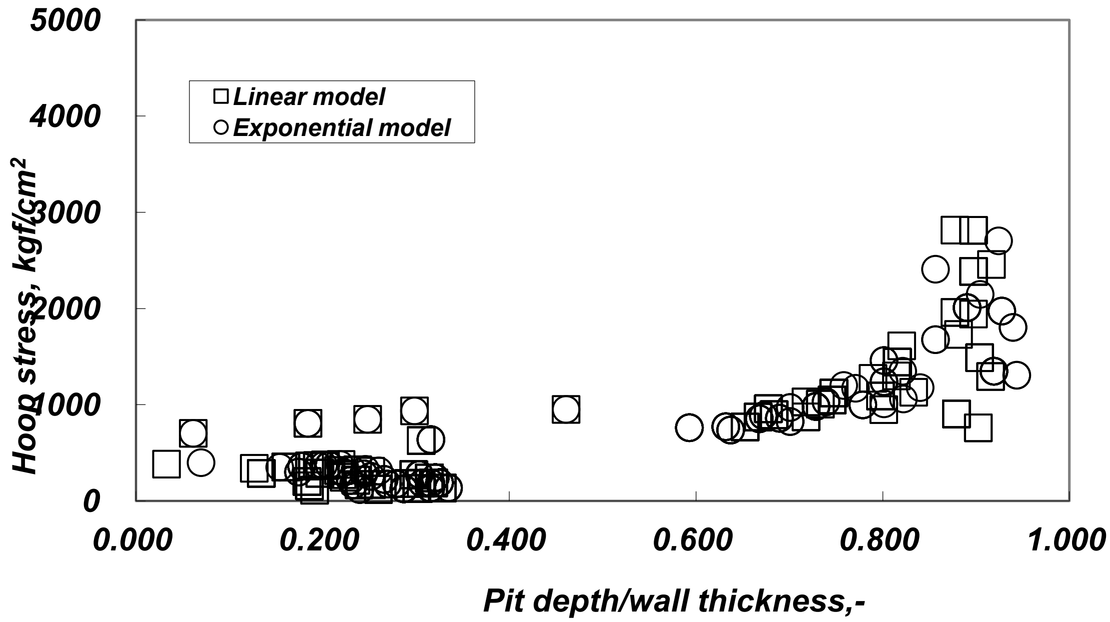


Figure 5.7 Estimation results of hoop stress by internal pressure

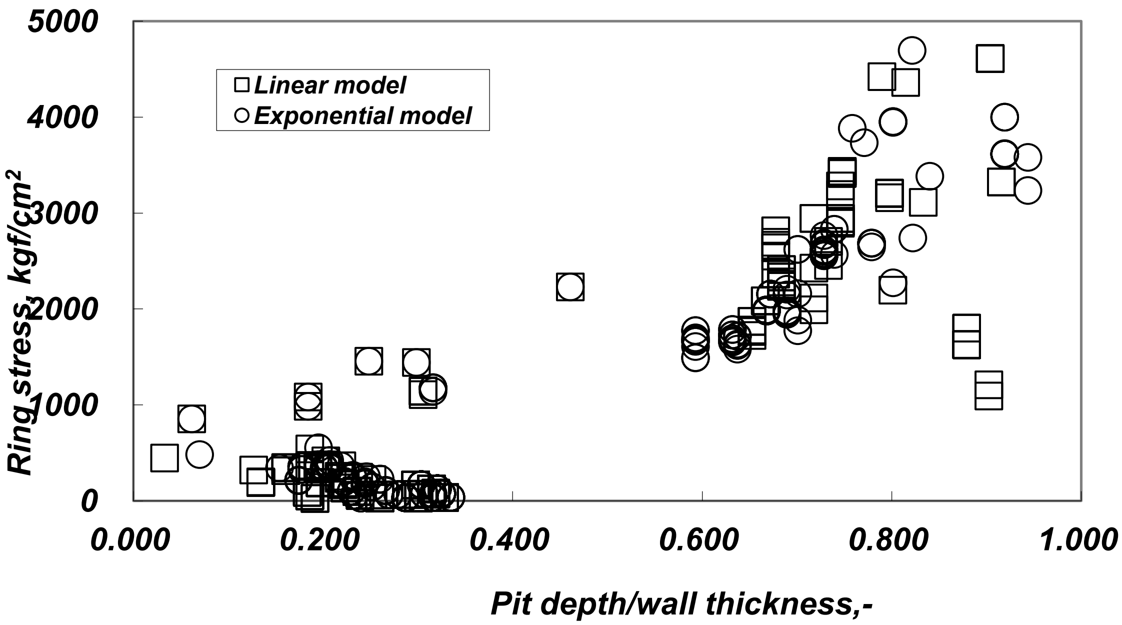


Figure 5.8 Estimation results of ring stress by external load

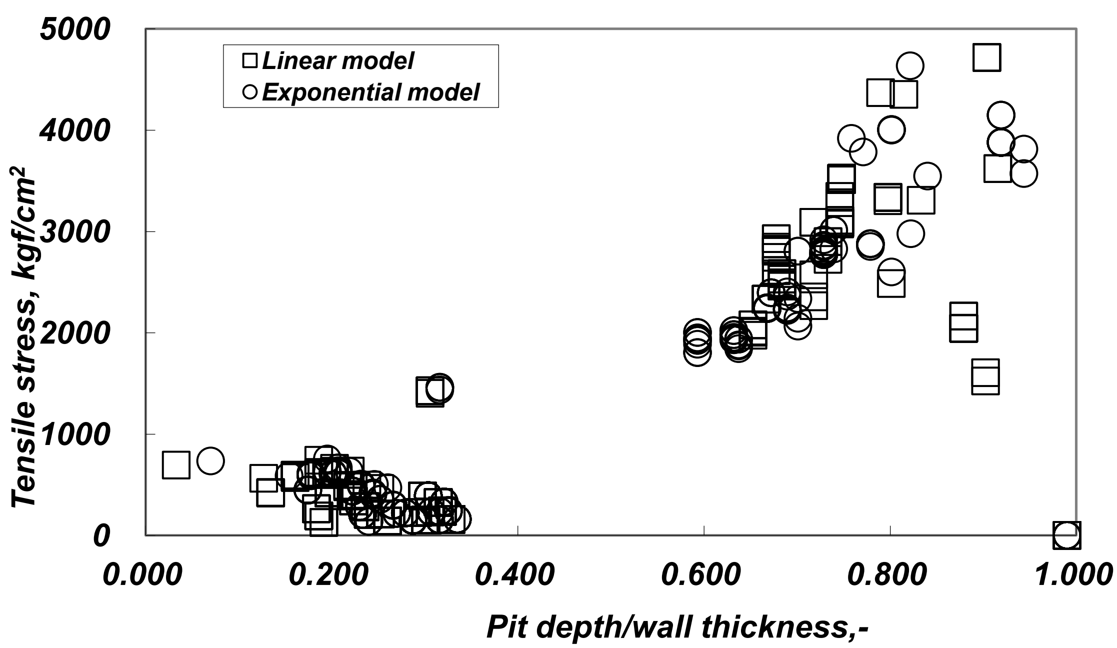
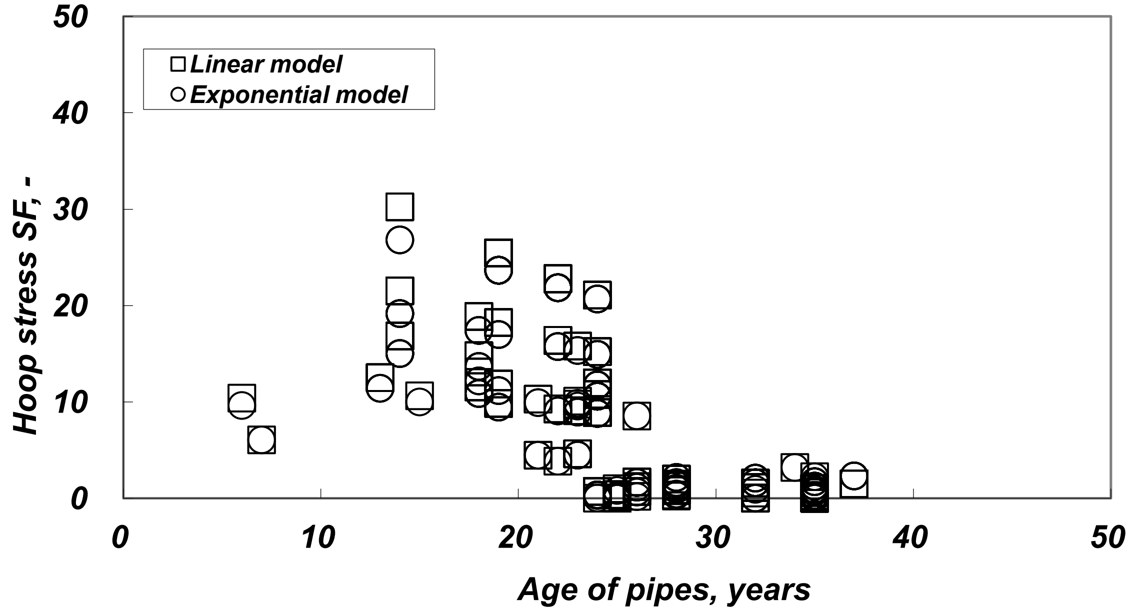


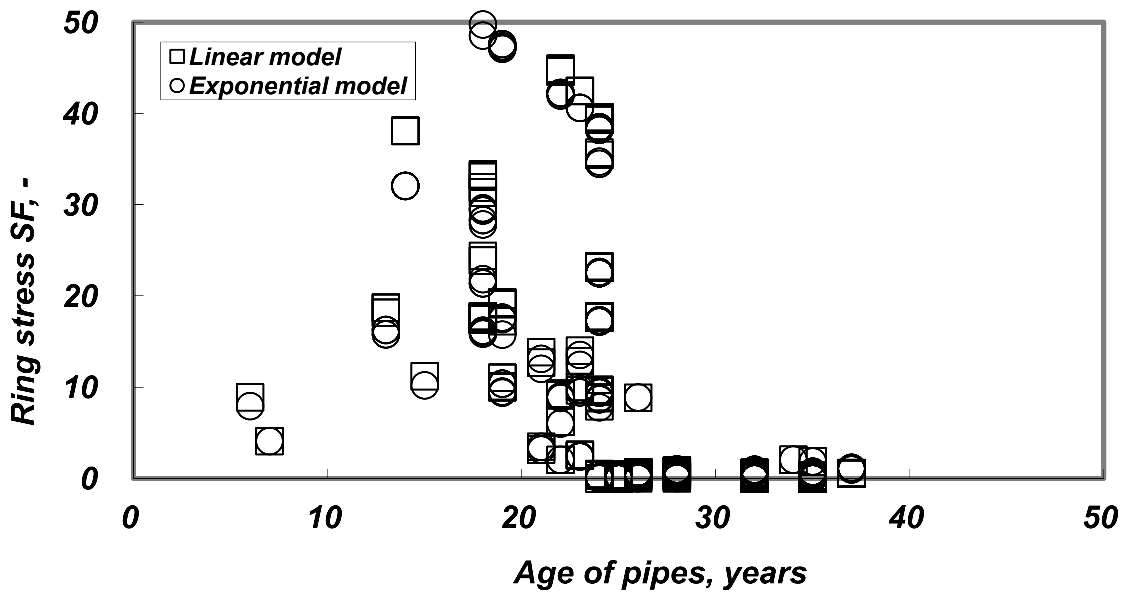
Figure 5.9 Estimation results of tensile stress by internal pressure and external load

5.3.5 Estimation of Safety Factor

Figure 5.10 shows hoop stress by internal pressure and the safety factor for tensile stress that considered external load among the water pipes in the Changwon, South Korea, area. Some of the water pipes laid before 1985 recorded an SF of 1, and the pipes whose corrosion percentage was over 1 recorded an SF of 0. According to the results of SF estimation based on the linear model, a total of 192 sections had a hoop stress SF that was lower than 1 by internal pressure, and 249 sections had a tensile stress SF that considered external load and internal load. Thus, 35.97% of the total 712 sections had a high failure risk according to the tensile stress SF that considered both internal pressure and stress for external load. When the exponential model was applied, the number of those two sections was 155 and 249, respectively, which means 35.97% had a high failure risk. Therefore, 249 sections of DCIPs were required to be replaced. It means that the length of the pipes to be replaced was 32,663 km of a total of 66,279 km. SFs of Steel pipes are larger than 1 for both internal pressure and external load with respect to both linear and exponential models.

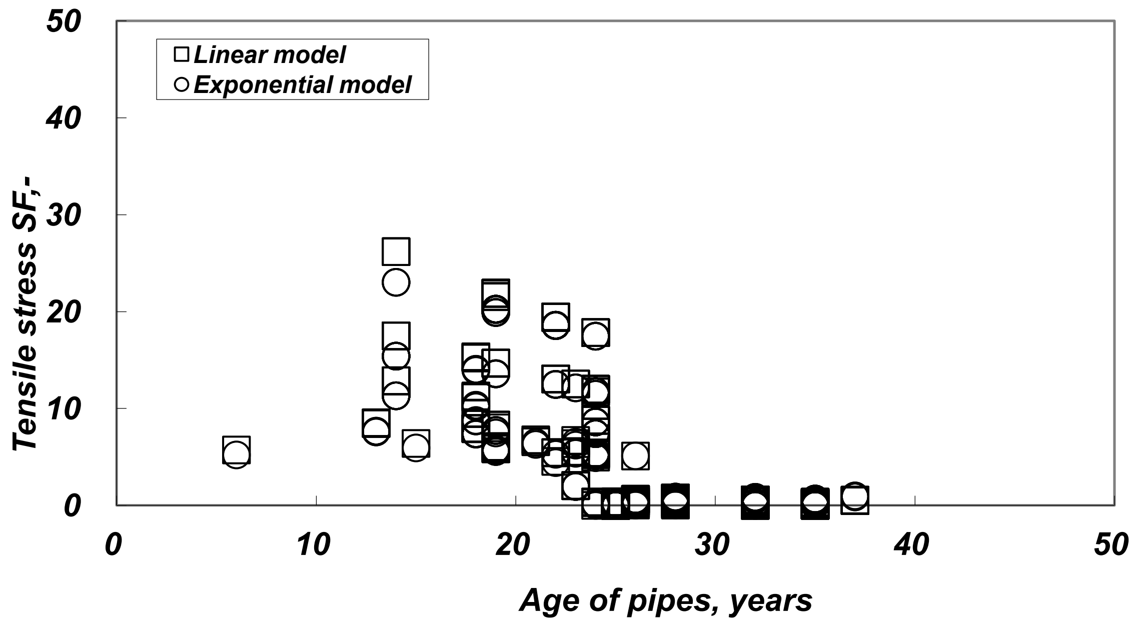


(a) Hoop stress SF



(b) Ring stress SF

Figure 5.10 Estimation results of the safety factor of Changwon, South Korea,water pipes



(c) Tensile stress SF

Figure 5.10 Continued

6. CONCLUSION

Today the life of a pipe is determined by assessing its useful life, economic value and risk of physical failure. The criteria to make physical judgments about failure risk or the criteria of life expectancy are set based on the assessment of the “safety factor.” That is, one can estimate life expectancy by estimating the safety factor.

This study developed a model to estimate the life expectancy and residual life of a pipe based on the assessment of failure risk in order to evaluate the current failure possibility and predict when the pipe would reach the point of failure. The model development was based on a database (containing data from 178 locations) containing data from the preventive inspections by K-Water and the survey of pipe deterioration among local water pipes. The developed model for estimation of residual life by failure risk was used to assess the failure risk of water pipes based on the general data and pipe sources of the Changwon, South Korea,water pipes and the results were as follows:

First, a residual thickness model to predict the growth of internal and external corrosion depth was proposed, and the life of major coating materials used as internal and external coating materials was estimated in order to implement a prediction model for physical damage risk to cast iron pipes and steel pipes, which were part of the metal pipes used in water pipes.

The measurements of internal and external corrosion depth indicate that internal corrosion caused by contact with water inflicted two times as much damage as external corrosion caused by contact with soil in Korea, which is because the corrosion of water pipes is under the greater influence of water quality than corrosion. Thus it is important to control internal corrosion for the sake of pipe maintenance.

A linear or non-linear model was proposed according to the ways corrosion would progress in a prediction model for residual thickness. The non-linear model predicted greater growth of corrosion depth than the linear model in the early days of installation. As the years of installation grew, the linear model tended to predict greater growth of corrosion depth than the non-linear model. However, there has been no evident conclusion drawn as to which model will be a more valid choice. For the time being, it seems safe to apply a non-linear model rather than a linear one in the early days of installation as the pipes directly contact the influencers of internal and external corrosion, thus undergoing corrosion fast, in the early days of installation; then the corrosion products deter corrosion progress between water and the pipe surface according to the passage of time.

The life of cement mortar lining in cast iron pipes or that of internal and external coating materials in steel pipes is estimated to be over 30 years according to the CML criteria. The life of coal tar enamel, a major internal and external coating material in the past, is estimated to be 13 years according to the exfoliation criteria and 25 years according to the EIS criteria. External coal tar enamel loses its anti-corrosive efficacy after 25 years of installation according to the EIS criteria. Steel pipes start to corrode after 25 years of installation, which means there should be close monitoring and maintenance measures for the inside and outside of steel pipes.

The measurements of residual strength in cast iron pipes and steel pipes reveal that there were rather big deviations in pure metal strength, due to huge differences in the quality of pipes manufactured in the past among different manufacturers. As the corrosion ratio grew, the residual strength of the pipe body tended to decrease in a linear fashion. Considering that there is a variety of stress on pipes according to load, it is required to assess circumference- or axis-oriented flexural strength to evaluate resistance against destruction according to more diverse types of stress than residual tensile strength and to predict physical damage risk more accurately.

Secondly, the model for estimation of residual life by failure risk was applied to the Changwon, South Korea,water pipes. As a result, some of the water pipes laid before 1985 had an SF of 1 or lower, and the pipes whose corrosion percentage was over 1 reached an SF of 0. When it was assumed that corrosion would increase in a linear fashion based on the tensile stress SF for tensile stress that considered both internal pressure and stress for external load, 35.97% of a total of 718 sections turned out to have a high failure risk or to have reached the end of their life (SF<1).

Based on the direct evaluation results according to the pipe conditions by K-Water, the sections whose SF is 1 or lower mostly need “replacement”; the sections whose SF is 1.0~2.5 need structural reinforcement; and the sections whose SF is 2.5 or higher need epoxy lining. According to the application results of a physical damage risk prediction model to Changwon, South Korea, most of the ductile cast iron pipes with no lining recorded 1 or lower in SF and reached the corrosion state where structural reinforcement would not be enough, thus needing “replacement.” The ductile cast irons with cement mortar lining and steel pipes were in a good condition in terms of CML and internal coating material, recorded 2.5 or higher in SF, needed no rehabilitation, and were good for continued use.

In Korea, the efforts to diagnose and evaluate water pipes are limited to the assessment of current pipe conditions, which is why one can easily determine the priority of rehabilitation based on the current pipe conditions but has a hard time getting information about how the pipes have deteriorated to the point of requiring rehabilitation. There is a need to develop a model for estimation of residual life or to estimate future pipe conditions based on gathered information and data analysis. Estimation of residual life can especially help make short-, mid- or long-term rehabilitation plans as to when to start a pipe rehabilitation project, since it identifies a section of short residual life, determines the priority, and estimates a rehabilitation point based on residual life. Thus, results of this study are expected to help make efficient rehabilitation plans based on risk of failure and estimation of residual life for the maintenance of K-Water water pipes.

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APPENDIX

1. Data of maximum pit depth of pipe according to years of laying (DIP/DCIP)

Pipe ID	Type	Diameter	Years	Max-pit(Ex)	Max-pit(In)	Max-pit(In)*-1
BY-2007-01	DIP	450	25	0	1.43	-1.43
CW-2001-01	DIP	400	19	5	6.3	-6.3
CW-2001-02	DIP	700	23		1.8	-1.8
CW-2001-03	DIP	700	26	0.9	6.3	-6.3
CW-2001-04	DIP	600	26	1.5	4.5	-4.5
CW-2003-01	DIP	700	28	1	2	-2
CW-2003-02	DIP	500	21	1.3	1.9	-1.9
CW-2004-01	DIP	600	29	2		
CW-2004-03	DIP	600	29	0.8	2.9	-2.9
DC-2004-01	DCIP	300	17	0	0	0
DC-2004-02	DCIP	700	17	0	0	0
DC-2004-03	DCIP	250	17	0	0	0
GJ-2001-01	DIP	350	22	0	1.9	-1.9
GJ-2001-02	DIP	250	16	0	6.7	-6.7
GJ-2001-03	DIP	450	22		2	-2
GJ-2002-01	DCIP	300	7	0	0	0
GJ-2003-01	DCIP	450	24			
GJ-2003-03	DIP	300	24	0	4	-4
GJ-2004-01	DCIP	450	9	0	0	0
GJ-2004-02	CIP	450	25	0	8.3	-8.3
GJ-2007-01	CIP	250	22	1.35	2.12	-2.12
GJ-2007-02	DIP	350	28	2.42	3.47	-3.47

1. Continued

GJ-2007-03	DCIP	300	9	2.53	0	0
KK-2005-02	DCIP	500	21	0	0	0
KM-2002-01	DIP	400	23	2.9	4.5	-4.5
KM-2002-02	DCIP	350	6	0	0	0
KM-2003-01	DCIP	600	6	0	0	0
KM-2003-02	DIP	500	21	0	4	-4
KM-2007-01	DIP	400	24	0	3.22	-3.22
KM-2007-02	DIP	400	24	1.31	3.41	-3.41
KM-2007-03	DIP	500	24	1.51	3.4	-3.4
NK-2005-01	DCIP	600	16		0	0
NK-2005-02	DCIP	600	16		0	0
YS-2004-01	DCIP	450	10		0	0
CW-C-1	DIP	200	21	2.64	4.77	-4.77
CW-C-6	DIP	100	21	0.16	5.12	-5.12
CW-C-2	DIP	150	20	1.52	5.25	-5.25
CW-C-3	DIP	150	19	1.19	7.3425	-7.3425
CW-D-6	DIP	100	19	2.06	2.49	-2.49
CW-D-1	DCIP	200	18	1.78	0	0
CW-D-2	DCIP	100	18	0.61	0	0
CW-D-3	DCIP	400	13	0	0	0
CW-D-4	DCIP	100	8	1.59	0	0
CW-C-5	DIP	900	22	0	3.45	-3.45
CW-C-4	DIP	500	22	0	8.47	-8.47
CW-D-5	DCIP	600	18	0	0	0

1. Continued

SC-D-1	DCIP	250	20	5.66	0	0
SC-D-2	DCIP	250	20	2.87	0	0
GJ-080610	DIP	450	29	7.12	5.56	-5.56
GJ-080618	DIP	250	23	4.85	2.84	-2.84
GJ-080710	DIP	450	29	0	6.28	-6.28
US-080816	DIP	1200	44	5.75	5.09	-5.09
CW-A	DCIP	400	19	1.62	0	0
CW-B	DIP	400	26	3.74	6.22	-6.22
CW-C	DCIP	400	11	3.64	0	0
CW-D	DIP	600	33	3.53	8.99	-8.99
CW-E	DIP	100	21	4.78	5.6	-5.6
CW-F	DIP	400	30	2.67	5.81	-5.81
CW-G-2	DIP	600	33	3.59	9.44	-9.44
CW-H	DIP	500	26	4.66	9.47	-9.47
CW-I-1	DIP	600	26	0.99	8.61	-8.61
CW-I-2	DIP	600	26	0.99	8.61	-8.61
CW-J	DCIP	600	20	3.02	0	0
CW-K	DIP	600	33	2.42	7.35	-7.35
CW-L	DIP	600	30	3.24	6.63	-6.63
GUM-4	DIP	300	27	0.7	2.83	-2.83
GUM-4-1	DIP	400	27	0.8	1.16	-1.16
TB-3	DCIP	300		1.8		
BY-1	DCIP	500	25	1.56	0	0
BY-2	DCIP	700	10	0.88	0	0
G-2	CIP	600	42	2.42	4.87	-4.87
H	DIP	900	30	1	6.36	-6.36
BA-KC-01	DCIP	600	12	0.59	0	0
BA-KC-02	DCIP	400	12	1.4	0	0

1. Continued

JJ-KK-01	DCIP	450	7	0	0	0
CH-BY-238	DCIP	400	13	1.32	0	0
CW-DS-01	CIP	600	43	2.64	4.99	-4.99
BY-DIP-011	DIP	400	27	3.41	5.33	-5.33
CHA-DCIP-01	DCIP	700	12	0.2	0	0

2. Data of maximum pit depth of pipe according to years of laying (SP)

Pipe ID	**Type**	**Diameter**	**Years**	**Max-pit(Ex)**	**Max-pit(In)**	**Max-pit(In)*-1**
BR-2004-01	SP	1650	6	0		
CW-2002-02	SP	1100	37	0	3	-3
CW-2004-04	SP	800	13	0	0	0
CW-2005-01	SP	1100	28			
CW-2005-02	SP	1100	28			
CW-2007-01	SP	800	40			
CW-2007-02	SP	1350	32	0	0.81	-0.81
GJ-2003-02	SP	450	24	0	0	0
KK-2003-01	SP	1500	19	0	0	0
KK-2003-02	SP	1500	19	0		
KK-2005-01	SP	1500	20	0	0.3	-0.3
KM-2004-01	SP	600	22	0		
KS-2002-01	SP	1200	9	0	0	0
MP-2005-01	SP	1100	12	0	0	0

2. Continued

MP-2005-02	SP	1100	12		0	0
NG-2002-01	SP	1100	13	0	0	0
NG-2002-02	SP	900	13	0		
NG-2002-03	SP	800	13	0	0	0
NG-2003-01	SP	900	16	0	0	0
NG-2003-02	SP	800	16	0	0	0
PD-2007-01	SP	2200	28		3.28	-3.28
PH-2002-01	SP	1350	22			
PH-2004-01	SP	1000	33			
PH-2007-01	SP	1350	26	1.28		
SC-2007-03	SP	900	18	0	0	0
SO-2002-01	SP	2200	23	0	0	0
SO-2004-01	SP	2800	26	0	0	0
SO-2004-02	SP	2200	25	0	0	0
SO-2006-01	SP	1800	22	0	0	0
SO-2006-02	SP	1800	22	0	0	0
TB-2003-01	SP	500	2			
US-2003-01	SP	1200	6	0	0	0
US-2003-02	SP	1100	12			
US-2003-03	SP	1100	7			
US-2003-04	SP	1200	39			

2. Continued

US-2003-05	SP	900	25			
US-2005-01	SP	900	29	0	5.6	-5.6
US-2006-01	SP	900	40		1.8	-1.8
US-2007-01	SP	1100	16			
US-2007-02	SP	900	29	2.38	2.38	-2.38
US-2007-03	SP	900	29	0		
US-2007-04	SP	200	26	1.46	3.28	-3.28
US-2007-05	SP	1350	31	1.29	3.42	-3.42
YH-2003-01	SP	2000	11	0		
YH-2003-02	SP	900	6	0		
YH-2006-01	SP	1650	28	0	1.8	-1.8
YH-2006-02	SP	1650	28	0	0	0
YS-2004-02	SP	900	20			
YS-2005-01	SP	1500	16	0	0	0
YS-2007-01	SP	900	17			
C-S-1	SP	350	19		2.36	-2.36
CW(2)-S-1	SP	1200	32	0	0	0
CW(2)-S-2	SP	1100	32	0	2.82	-2.82
CW(2)-S-3	SP	1100	32	0	2.4	-2.4
SDII-S-1	SP	2000	27	0	1	-1
SDII-S-2	SP	2000	27	0	1	-1
SDII-S-3	SP	2000	27	0	1	-1
SDII-S-4	SP	2000	27	0	1	-1

2. Continued

SDII-S-5	SP	2000	27	0	0.77	-0.77
USOS-S-1	SP	1200	15		2.26	-2.26
USOS-S-2	SP	1200	15		2.26	-2.26
USOS-S-3	SP	900	14		2.26	-2.26
USOS-S-4	SP	1000	14		1.91	-1.91
YCH-S-A	SP	900	21	0	0	0
YCH-S-C	SP	1650	32	0	1.06	-1.06
YCSP-S-1	SP	1650	33		6.11	-6.11
YCSP-S-2	SP	1650	33	0	2.8	-2.8
CW-G-1	SP	600	33	2.28	3.51	-3.51
CW-M	SP	1350	34	0	0	0
GUM-5	SP	600	24	0	0.47	-0.47
BY-3	SP	1500	28	0	1.24	-1.24
DC-SP-1	SP	1100	22	0	0	0
IS-1	SP	1500	26	0	1.49	-1.49
IS-2-1	SP	1500	26	0	2.48	-2.48
IS-3	SP	1100	25	0	1.97	-1.97
S3-SP-1	SP	1100	21	0	0	0
S3-SP-2	SP	1100	21	0	0	0
YS-SP-1	SP	1500	10	0	0	0
F	SP	1100	33	0	0.27	-0.27
A	SP	1350	34	0	2.02	-2.02
J	SP	1100	35	1.61	1.82	-1.82
G-1	SP	800	42	0	2.64	-2.64
B	SP	1650	34	2.36	1.78	-1.78
C	SP	1100	43	0	1.02	-1.02
D	SP	1100	43	0	1.14	-1.14
A	SP	1350	32	0	0.79	-0.79
DH-JS-01	SP	300	11	0	1.72	-1.72

2. Continued

SD-IV-01	SP	2400	19	0	1.14	-1.14
SD-Ⅱ-1100	SP	1100	30		1.64	-1.64
SD-Ⅱ-1500	SP	1500	30		1.02	-1.02
SD-Ⅱ-1TOUT	SP	2400	30		2.43	-2.43
SD-Ⅱ-2TIN	SP	2400	30		4.25	-4.25
SD-Ⅱ-2TOUT	SP	2400	30		3.04	-3.04
SD-Ⅱ-3TIN	SP	2400	30		2.4	-2.4
SD-Ⅲ-01	SP	1350	23		1.52	-1.52
US-OS-02	SP	1200	17	0	1.53	-1.53
TB-DB-01	SP	1000	21	0.5	1.44	-1.44
TB-DB-02	SP	1000	7	0	0	0
JA-MP-01	SP	1200	15	0	0	0

3. Data of each method of SF (DCIP)

No.	Type	Years	linear (Hoop)	exponential (Hoop)	linear (Ring)	exponential (Ring)	linear (Tensile)	exponential (Tensile)
1	DCIP	15	10.635	9.995	11.213	10.210	6.391	5.931
2	DCIP	24	11.978	11.764	23.275	22.646	8.806	8.627
3	DCIP	24	15.216	14.937	39.600	38.508	11.991	11.747
4	DCIP	24	10.774	10.595	17.781	17.337	7.565	7.421
5	DCIP	24	15.216	14.937	39.596	38.504	11.990	11.747
6	DCIP	24	10.774	10.595	17.779	17.335	7.565	7.420
7	DCIP	24	10.774	10.595	17.778	17.334	7.565	7.420

3. Continued

8	DCIP	24	10.774	10.595	17.777	17.333	7.565	7.420
9	DCIP	24	21.086	20.683	81.036	78.705	17.837	17.470
10	DCIP	24	15.216	14.937	39.585	38.494	11.990	11.747
11	DCIP	24	10.774	10.595	17.775	17.330	7.564	7.420
12	DCIP	24	8.901	8.812	9.586	9.441	5.394	5.330
13	DCIP	24	8.901	8.812	9.586	9.441	5.394	5.330
14	DCIP	24	8.901	8.812	9.585	9.441	5.394	5.330
15	DCIP	24	8.901	8.812	9.585	9.440	5.394	5.329
16	DCIP	24	8.901	8.812	9.585	9.440	5.394	5.329
17	DCIP	24	8.901	8.812	9.585	9.440	5.394	5.329
18	DCIP	24	8.901	8.812	9.584	9.440	5.394	5.329
19	DCIP	24	8.901	8.812	9.584	9.439	5.394	5.329
20	DCIP	24	8.901	8.812	9.584	9.439	5.394	5.329
21	DCIP	24	8.901	8.812	9.584	9.439	5.394	5.329
22	DCIP	24	8.901	8.812	9.583	9.439	5.394	5.329
23	DCIP	24	8.901	8.812	9.583	9.438	5.394	5.329
24	DCIP	23	9.086	8.940	10.035	9.793	5.561	5.454
25	DCIP	24	8.901	8.812	9.582	9.438	5.394	5.329
26	DCIP	24	15.216	14.937	39.552	38.462	11.987	11.744
27	DCIP	24	15.216	14.937	39.550	38.460	11.987	11.744
28	DCIP	24	15.216	14.937	35.714	34.730	11.720	11.481
29	DCIP	18	14.794	13.679	33.350	29.621	11.288	10.337
30	DCIP	18	14.794	13.679	33.224	29.509	11.278	10.328
31	DCIP	18	18.870	17.422	54.778	48.543	15.204	13.924
32	DCIP	18	18.870	17.422	56.154	49.762	15.276	13.993
33	DCIP	18	18.870	17.422	57.355	50.827	15.338	14.051
34	DCIP	18	13.106	12.185	23.884	21.389	9.469	8.711
35	DCIP	18	13.106	12.185	23.883	21.388	9.469	8.711
36	DCIP	18	13.106	12.185	24.400	21.852	9.525	8.764
37	DCIP	23	4.618	4.484	2.537	2.427	2.031	1.955
38	DCIP	23	4.618	4.484	2.537	2.427	2.031	1.955
39	DCIP	18	11.570	10.873	17.800	16.204	7.952	7.398
40	DCIP	18	11.570	10.873	17.633	16.052	7.928	7.376
41	DCIP	18	11.570	10.873	17.782	16.188	7.949	7.396
42	DCIP	24	8.901	8.812	9.578	9.433	5.393	5.328
43	DCIP	24	8.901	8.812	8.931	8.796	5.243	5.179
44	DCIP	24	8.901	8.812	9.725	9.578	5.425	5.360
45	DCIP	24	8.901	8.812	9.712	9.565	5.422	5.357
46	DCIP	24	8.901	8.812	8.811	8.678	5.214	5.151

3. Continued

47	DCIP	24	8.901	8.812	7.925	7.805	4.983	4.922
48	DCIP	24	15.216	14.937	39.507	38.418	11.985	11.742
49	DCIP	24	15.216	14.937	39.505	38.416	11.984	11.741
50	DCIP	24	15.216	14.937	39.503	38.414	11.984	11.741
51	DCIP	24	15.216	14.937	39.501	38.412	11.984	11.741
52	DCIP	24	10.774	10.595	17.737	17.294	7.560	7.415
53	DCIP	24	10.774	10.595	17.736	17.293	7.559	7.415
54	DCIP	24	10.774	10.595	17.735	17.292	7.559	7.415
55	DCIP	24	10.774	10.595	17.734	17.291	7.559	7.415
56	DCIP	24	10.774	10.595	17.733	17.290	7.559	7.415
57	DCIP	24	10.774	10.595	17.732	17.289	7.559	7.415
58	DCIP	24	10.774	10.595	17.731	17.288	7.559	7.414
59	DCIP	24	10.774	10.595	17.731	17.287	7.559	7.414
60	DCIP	24	10.774	10.595	17.730	17.286	7.559	7.414
61	DCIP	24	10.774	10.595	17.729	17.286	7.558	7.414
62	DCIP	24	10.774	10.595	17.728	17.285	7.558	7.414
63	DCIP	24	10.774	10.595	17.727	17.284	7.558	7.414
64	DCIP	24	10.774	10.595	17.726	17.283	7.558	7.414
65	DCIP	24	10.774	10.595	17.725	17.282	7.558	7.414
66	DCIP	24	10.774	10.595	17.724	17.281	7.558	7.414
67	DCIP	24	10.774	10.595	17.723	17.280	7.558	7.413
68	DCIP	24	10.774	10.595	17.722	17.279	7.558	7.413
69	DCIP	24	10.774	10.595	17.721	17.278	7.558	7.413
70	DCIP	24	10.774	10.595	17.720	17.278	7.557	7.413
71	DCIP	24	10.774	10.595	17.720	17.277	7.557	7.413
72	DCIP	24	15.216	14.937	39.458	38.370	11.981	11.738
73	DCIP	24	21.086	20.683	80.765	78.442	17.828	17.461
74	DCIP	24	21.086	20.683	80.761	78.438	17.827	17.460
75	DCIP	24	21.086	20.683	80.757	78.434	17.827	17.460
76	DCIP	24	21.086	20.683	80.753	78.430	17.827	17.460
77	DCIP	24	21.086	20.683	80.749	78.426	17.827	17.460
78	DCIP	24	21.086	20.683	80.744	78.422	17.827	17.460
79	DCIP	24	10.774	10.595	17.712	17.270	7.556	7.412
80	DCIP	24	10.774	10.595	17.711	17.269	7.556	7.412
81	DCIP	24	10.774	10.595	17.710	17.268	7.556	7.412
82	DCIP	24	10.774	10.595	17.710	17.267	7.556	7.412
83	DCIP	24	10.774	10.595	17.709	17.266	7.556	7.412
84	DCIP	24	10.774	10.595	17.708	17.265	7.556	7.411

3. Continued

85	DCIP	24	10.774	10.595	17.707	17.264	7.556	7.411
86	DCIP	24	10.774	10.595	17.706	17.263	7.556	7.411
87	DCIP	18	11.570	10.873	17.610	16.031	7.925	7.373
88	DCIP	18	11.570	10.873	17.751	16.159	7.945	7.392
89	DCIP	18	11.570	10.873	17.700	16.113	7.938	7.385
90	DCIP	18	11.570	10.873	17.670	16.086	7.933	7.381
91	DCIP	18	11.570	10.873	17.749	16.157	7.944	7.391
92	DCIP	18	14.794	13.679	31.891	28.325	11.167	10.223
93	DCIP	18	14.794	13.679	31.352	27.846	11.120	10.179
94	DCIP	18	14.794	13.679	31.888	28.322	11.167	10.223
95	DCIP	24	15.216	14.937	39.411	38.324	11.978	11.735
96	DCIP	24	15.216	14.937	39.409	38.322	11.978	11.735
97	DCIP	24	15.216	14.937	39.407	38.320	11.978	11.735
98	DCIP	24	15.216	14.937	39.405	38.318	11.978	11.735
99	DCIP	24	15.216	14.937	39.403	38.316	11.978	11.735
100	DCIP	24	15.216	14.937	39.401	38.314	11.978	11.735
101	DCIP	24	10.774	10.595	17.692	17.250	7.554	7.410
102	DCIP	24	10.774	10.595	17.691	17.249	7.554	7.409
103	DCIP	24	10.774	10.595	17.690	17.248	7.554	7.409
104	DCIP	24	10.774	10.595	17.689	17.247	7.553	7.409
105	DCIP	24	10.774	10.595	17.689	17.246	7.553	7.409
106	DCIP	24	10.774	10.595	17.688	17.246	7.553	7.409
107	DCIP	24	10.774	10.595	17.687	17.245	7.553	7.409
108	DCIP	24	10.774	10.595	17.686	17.244	7.553	7.409
109	DCIP	24	10.774	10.595	17.685	17.243	7.553	7.409
110	DCIP	24	10.774	10.595	17.684	17.242	7.553	7.408
111	DCIP	24	10.774	10.595	17.683	17.241	7.553	7.408
112	DCIP	24	15.216	14.937	39.376	38.290	11.976	11.733
113	DCIP	24	15.216	14.937	39.374	38.288	11.976	11.733
114	DCIP	24	15.216	14.937	39.372	38.286	11.976	11.733
115	DCIP	24	11.978	11.764	23.139	22.514	8.792	8.613
116	DCIP	24	11.978	11.764	23.138	22.513	8.792	8.613
117	DCIP	24	11.978	11.764	23.137	22.512	8.792	8.613
118	DCIP	24	11.978	11.764	23.136	22.510	8.792	8.613
119	DCIP	24	11.978	11.764	23.134	22.509	8.792	8.613
120	DCIP	24	11.978	11.764	23.133	22.508	8.792	8.613
121	DCIP	24	11.978	11.764	23.132	22.507	8.792	8.613
122	DCIP	24	11.978	11.764	23.131	22.506	8.791	8.613

3. Continued

123	DCIP	24	11.978	11.764	23.130	22.505	8.791	8.612
124	DCIP	24	11.978	11.764	23.128	22.504	8.791	8.612
125	DCIP	24	11.978	11.764	23.127	22.502	8.791	8.612
126	DCIP	24	11.978	11.764	23.126	22.501	8.791	8.612
127	DCIP	24	11.978	11.764	23.125	22.500	8.791	8.612
128	DCIP	24	11.978	11.764	23.124	22.499	8.791	8.612
129	DCIP	24	11.978	11.764	23.122	22.498	8.791	8.612
130	DCIP	24	11.978	11.764	23.121	22.497	8.791	8.612
131	DCIP	24	10.774	10.595	17.665	17.223	7.550	7.406
132	DCIP	24	10.774	10.595	17.664	17.223	7.550	7.406
133	DCIP	24	10.774	10.595	17.663	17.222	7.550	7.406
134	DCIP	24	10.774	10.595	17.662	17.221	7.550	7.406
135	DCIP	24	10.774	10.595	17.661	17.220	7.550	7.406
136	DCIP	24	10.774	10.595	17.660	17.219	7.550	7.405
137	DCIP	24	10.774	10.595	17.659	17.218	7.550	7.405
138	DCIP	24	15.216	14.937	39.323	38.239	11.973	11.730
139	DCIP	23	4.618	4.484	2.616	2.501	2.065	1.989
140	DCIP	18	11.570	10.873	17.583	16.007	7.921	7.369
141	DCIP	23	4.618	4.484	2.531	2.421	2.028	1.952
142	DCIP	24	8.901	8.812	9.552	9.407	5.387	5.322
143	DCIP	24	8.901	8.812	9.551	9.407	5.387	5.322
144	DCIP	24	15.216	14.937	39.311	38.227	11.972	11.729
145	DCIP	24	10.774	10.595	17.652	17.211	7.549	7.404
146	DCIP	18	18.870	17.422	57.154	50.649	15.327	14.041
147	DCIP	18	18.870	17.422	57.183	50.674	15.329	14.043
148	DCIP	24	15.216	14.937	35.472	34.493	11.702	11.463
149	DCIP	24	15.216	14.937	39.301	38.217	11.971	11.728
150	DCIP	18	14.794	13.679	33.061	29.365	11.265	10.315
151	DCIP	23	9.086	8.940	9.670	9.436	5.481	5.375
152	DCIP	23	4.618	4.484	2.530	2.420	2.028	1.952
153	DCIP	18	11.570	10.873	17.568	15.992	7.919	7.367
154	DCIP	18	11.570	10.873	17.440	15.876	7.901	7.350
155	DCIP	24	8.901	8.812	9.669	9.523	5.413	5.348
156	DCIP	24	10.774	10.595	17.642	17.201	7.547	7.403
157	DCIP	22	22.785	21.852	92.857	87.158	19.445	18.589
158	DCIP	22	22.785	21.852	92.852	87.154	19.445	18.589
159	DCIP	22	22.785	21.852	92.848	87.150	19.445	18.589
160	DCIP	22	22.785	21.852	92.844	87.145	19.445	18.589

3. Continued

161	DCIP	22	22.785	21.852	92.839	87.141	19.445	18.589
162	DCIP	22	22.785	21.852	92.835	87.137	19.444	18.589
163	DCIP	19	25.458	23.662	109.807	98.298	21.903	20.250
164	DCIP	19	25.458	23.662	109.802	98.293	21.903	20.250
165	DCIP	19	25.458	23.662	109.796	98.289	21.903	20.250
166	DCIP	26	8.536	8.558	8.847	8.881	5.095	5.110
167	DCIP	19	25.458	23.662	109.786	98.280	21.903	20.250
168	DCIP	19	25.458	23.662	109.781	98.275	21.902	20.250
169	DCIP	19	25.458	23.662	109.776	98.271	21.902	20.249
170	DCIP	19	25.458	23.662	109.771	98.266	21.902	20.249
171	DCIP	19	25.458	23.662	109.766	98.261	21.902	20.249
172	DCIP	19	25.458	23.662	109.761	98.257	21.902	20.249
173	DCIP	19	25.458	23.662	109.756	98.252	21.902	20.249
174	DCIP	19	25.458	23.662	109.751	98.248	21.902	20.249
175	DCIP	19	18.233	16.996	52.961	47.614	14.693	13.598
176	DCIP	19	18.233	16.996	52.959	47.612	14.692	13.598
177	DCIP	19	11.857	11.179	19.283	17.638	8.289	7.743
178	DCIP	19	11.857	11.179	19.282	17.637	8.289	7.743
179	DCIP	22	22.785	21.852	92.762	87.069	19.442	18.587
180	DCIP	22	22.785	21.852	92.758	87.065	19.442	18.586
181	DCIP	22	22.785	21.852	92.753	87.061	19.442	18.586
182	DCIP	22	22.785	21.852	92.749	87.057	19.442	18.586
183	DCIP	22	22.785	21.852	92.745	87.053	19.442	18.586
184	DCIP	22	22.785	21.852	92.740	87.049	19.441	18.586
185	DCIP	22	22.785	21.852	92.736	87.045	19.441	18.586
186	DCIP	22	22.785	21.852	92.732	87.041	19.441	18.586
187	DCIP	22	22.785	21.852	92.728	87.037	19.441	18.586
188	DCIP	22	22.785	21.852	92.723	87.033	19.441	18.585
189	DCIP	22	22.785	21.852	92.719	87.028	19.441	18.585
190	DCIP	22	22.785	21.852	92.715	87.024	19.441	18.585
191	DCIP	22	22.785	21.852	92.710	87.020	19.441	18.585
192	DCIP	22	22.785	21.852	92.706	87.016	19.440	18.585
193	DCIP	22	22.785	21.852	92.702	87.012	19.440	18.585
194	DCIP	22	22.785	21.852	92.698	87.008	19.440	18.585
195	DCIP	22	22.785	21.852	92.693	87.004	19.440	18.585
196	DCIP	22	22.785	21.852	92.689	87.000	19.440	18.584
197	DCIP	22	22.785	21.852	92.685	86.996	19.440	18.584
198	DCIP	22	22.785	21.852	92.680	86.992	19.440	18.584

3. Continued

199	DCIP	22	22.785	21.852	92.676	86.988	19.440	18.584
200	DCIP	22	22.785	21.852	92.672	86.984	19.439	18.584
201	DCIP	22	22.785	21.852	92.668	86.980	19.439	18.584
202	DCIP	22	22.785	21.852	92.663	86.976	19.439	18.584
203	DCIP	22	22.785	21.852	92.659	86.972	19.439	18.584
204	DCIP	22	22.785	21.852	92.655	86.968	19.439	18.583
205	DCIP	22	22.785	21.852	92.650	86.964	19.439	18.583
206	DCIP	22	22.785	21.852	92.646	86.960	19.439	18.583
207	DCIP	22	22.785	21.852	92.642	86.956	19.438	18.583
208	DCIP	22	22.785	21.852	92.638	86.952	19.438	18.583
209	DCIP	22	22.785	21.852	92.633	86.948	19.438	18.583
210	DCIP	22	22.785	21.852	92.629	86.944	19.438	18.583
211	DCIP	22	22.785	21.852	92.625	86.940	19.438	18.583
212	DCIP	22	22.785	21.852	92.620	86.936	19.438	18.582
213	DCIP	22	22.785	21.852	92.616	86.932	19.438	18.582
214	DCIP	22	22.785	21.852	92.612	86.928	19.438	18.582
215	DCIP	22	22.785	21.852	92.608	86.924	19.437	18.582
216	DCIP	22	22.785	21.852	92.603	86.920	19.437	18.582
217	DCIP	22	22.785	21.852	92.599	86.916	19.437	18.582
218	DCIP	22	22.785	21.852	92.595	86.912	19.437	18.582
219	DCIP	22	22.785	21.852	92.590	86.908	19.437	18.581
220	DCIP	22	22.785	21.852	92.586	86.904	19.437	18.581
221	DCIP	22	22.785	21.852	92.582	86.900	19.437	18.581
222	DCIP	22	22.785	21.852	92.578	86.896	19.436	18.581
223	DCIP	22	22.785	21.852	92.573	86.892	19.436	18.581
224	DCIP	22	22.785	21.852	92.569	86.888	19.436	18.581
225	DCIP	22	22.785	21.852	92.565	86.884	19.436	18.581
226	DCIP	22	22.785	21.852	92.560	86.880	19.436	18.581
227	DCIP	22	22.785	21.852	92.556	86.876	19.436	18.580
228	DCIP	22	22.785	21.852	92.552	86.872	19.436	18.580
229	DCIP	22	22.785	21.852	92.548	86.868	19.436	18.580
230	DCIP	22	22.785	21.852	92.543	86.864	19.435	18.580
231	DCIP	22	22.785	21.852	92.539	86.860	19.435	18.580
232	DCIP	22	22.785	21.852	92.535	86.856	19.435	18.580
233	DCIP	22	22.785	21.852	92.531	86.852	19.435	18.580
234	DCIP	22	22.785	21.852	92.526	86.848	19.435	18.580
235	DCIP	22	22.785	21.852	92.522	86.844	19.435	18.579
236	DCIP	22	22.785	21.852	92.518	86.840	19.435	18.579

3. Continued

237	DCIP	22	22.785	21.852	92.513	86.836	19.434	18.579
238	DCIP	19	25.458	23.662	109.426	97.957	21.892	20.240
239	DCIP	19	25.458	23.662	109.421	97.953	21.892	20.240
240	DCIP	19	25.458	23.662	109.416	97.948	21.892	20.240
241	DCIP	19	25.458	23.662	109.411	97.944	21.892	20.240
242	DCIP	19	25.458	23.662	109.406	97.939	21.892	20.240
243	DCIP	19	25.458	23.662	109.401	97.935	21.892	20.239
244	DCIP	19	25.458	23.662	109.396	97.930	21.892	20.239
245	DCIP	19	25.458	23.662	109.391	97.926	21.891	20.239
246	DCIP	19	25.458	23.662	109.386	97.921	21.891	20.239
247	DCIP	19	25.458	23.662	109.381	97.917	21.891	20.239
248	DCIP	22	22.785	21.852	92.466	86.791	19.433	18.578
249	DCIP	23	15.797	15.339	42.478	40.625	12.534	12.132
250	DCIP	23	15.797	15.339	42.477	40.623	12.534	12.132
251	DCIP	23	15.797	15.339	42.475	40.621	12.534	12.132
252	DCIP	22	16.390	15.745	44.909	42.261	13.055	12.488
253	DCIP	22	16.390	15.745	44.907	42.259	13.055	12.488
254	DCIP	22	16.390	15.745	44.905	42.258	13.055	12.488
255	DCIP	22	22.785	21.852	92.437	86.763	19.432	18.577
256	DCIP	22	22.785	21.852	92.432	86.759	19.432	18.577
257	DCIP	22	22.785	21.852	92.428	86.755	19.432	18.577
258	DCIP	22	22.785	21.852	92.424	86.751	19.432	18.576
259	DCIP	22	22.785	21.852	92.420	86.747	19.432	18.576
260	DCIP	22	22.785	21.852	92.415	86.743	19.431	18.576
261	DCIP	22	22.785	21.852	92.411	86.739	19.431	18.576
262	DCIP	22	22.785	21.852	92.407	86.735	19.431	18.576
263	DCIP	22	22.785	21.852	92.402	86.731	19.431	18.576
264	DCIP	19	25.458	23.662	109.295	97.840	21.889	20.237
265	DCIP	19	25.458	23.662	109.290	97.835	21.889	20.236
266	DCIP	19	25.458	23.662	109.285	97.831	21.888	20.236
267	DCIP	19	25.458	23.662	109.280	97.826	21.888	20.236
268	DCIP	19	25.458	23.662	109.275	97.822	21.888	20.236
269	DCIP	19	25.458	23.662	109.270	97.817	21.888	20.236
270	DCIP	19	25.458	23.662	109.265	97.813	21.888	20.236
271	DCIP	19	25.458	23.662	109.260	97.808	21.888	20.236
272	DCIP	19	25.458	23.662	109.255	97.804	21.888	20.235
273	DCIP	19	25.458	23.662	109.250	97.799	21.887	20.235
274	DCIP	19	25.458	23.662	109.245	97.795	21.887	20.235

3. Continued

275	DCIP	19	25.458	23.662	109.240	97.790	21.887	20.235
276	DCIP	22	16.390	15.745	44.860	42.215	13.052	12.486
277	DCIP	22	16.390	15.745	44.858	42.213	13.052	12.485
278	DCIP	22	16.390	15.745	44.856	42.211	13.052	12.485
279	DCIP	22	16.390	15.745	44.854	42.209	13.052	12.485
280	DCIP	22	22.785	21.852	92.330	86.663	19.429	18.574
281	DCIP	22	22.785	21.852	92.326	86.659	19.429	18.574
282	DCIP	22	22.785	21.852	92.322	86.655	19.429	18.573
283	DCIP	22	22.785	21.852	92.317	86.651	19.428	18.573
284	DCIP	22	22.785	21.852	92.313	86.647	19.428	18.573
285	DCIP	22	22.785	21.852	92.309	86.643	19.428	18.573
286	DCIP	22	22.785	21.852	92.305	86.639	19.428	18.573
287	DCIP	22	22.785	21.852	92.300	86.635	19.428	18.573
288	DCIP	19	25.458	23.662	109.174	97.732	21.885	20.233
289	DCIP	19	25.458	23.662	109.169	97.727	21.885	20.233
290	DCIP	19	25.458	23.662	109.164	97.723	21.885	20.233
291	DCIP	19	25.458	23.662	109.159	97.718	21.885	20.233
292	DCIP	19	25.458	23.662	109.154	97.714	21.885	20.233
293	DCIP	19	25.458	23.662	109.149	97.709	21.885	20.233
294	DCIP	19	11.857	11.179	19.181	17.545	8.276	7.731
295	DCIP	19	18.233	16.996	52.670	47.352	14.677	13.583
296	DCIP	19	18.233	16.996	52.668	47.350	14.677	13.583
297	DCIP	19	18.233	16.996	52.665	47.348	14.677	13.583
298	DCIP	19	18.233	16.996	52.663	47.346	14.676	13.583
299	DCIP	19	25.458	23.662	109.119	97.682	21.884	20.232
300	DCIP	19	25.458	23.662	109.114	97.678	21.884	20.232
301	DCIP	19	25.458	23.662	109.109	97.673	21.884	20.232
302	DCIP	19	25.458	23.662	109.104	97.669	21.883	20.231
303	DCIP	19	25.458	23.662	109.099	97.664	21.883	20.231
304	DCIP	19	25.458	23.662	109.094	97.660	21.883	20.231
305	DCIP	19	25.458	23.662	109.089	97.655	21.883	20.231
306	DCIP	19	25.458	23.662	109.084	97.651	21.883	20.231
307	DCIP	19	25.458	23.662	109.079	97.646	21.883	20.231
308	DCIP	19	25.458	23.662	109.074	97.642	21.883	20.231
309	DCIP	19	25.458	23.662	109.069	97.637	21.882	20.230
310	DCIP	19	25.458	23.662	109.064	97.633	21.882	20.230
311	DCIP	19	25.458	23.662	109.059	97.628	21.882	20.230
312	DCIP	19	25.458	23.662	109.054	97.624	21.882	20.230

3. Continued

313	DCIP	19	25.458	23.662	109.049	97.619	21.882	20.230
314	DCIP	19	25.458	23.662	109.044	97.615	21.882	20.230
315	DCIP	19	25.458	23.662	109.039	97.610	21.882	20.230
316	DCIP	19	25.458	23.662	98.429	88.113	21.555	19.918
317	DCIP	19	25.458	23.662	109.029	97.601	21.881	20.229
318	DCIP	19	25.458	23.662	109.023	97.597	21.881	20.229
319	DCIP	19	25.458	23.662	109.018	97.592	21.881	20.229
320	DCIP	19	25.458	23.662	109.013	97.588	21.881	20.229
321	DCIP	19	25.458	23.662	109.008	97.583	21.881	20.229
322	DCIP	22	22.785	21.852	92.152	86.496	19.423	18.568
323	DCIP	22	22.785	21.852	92.147	86.492	19.423	18.568
324	DCIP	22	22.785	21.852	92.143	86.488	19.423	18.568
325	DCIP	22	22.785	21.852	92.139	86.484	19.423	18.568
326	DCIP	22	22.785	21.852	92.135	86.480	19.423	18.568
327	DCIP	22	22.785	21.852	92.130	86.476	19.423	18.568
328	DCIP	19	25.458	23.662	98.369	88.059	21.553	19.916
329	DCIP	22	22.785	21.852	92.122	86.468	19.422	18.567
330	DCIP	22	22.785	21.852	92.118	86.464	19.422	18.567
331	DCIP	22	22.785	21.852	92.114	86.460	19.422	18.567
332	DCIP	22	22.785	21.852	92.109	86.456	19.422	18.567
333	DCIP	22	22.785	21.852	92.105	86.452	19.422	18.567
334	DCIP	22	22.785	21.852	92.101	86.448	19.422	18.567
335	DCIP	22	22.785	21.852	92.097	86.444	19.422	18.567
336	DCIP	22	22.785	21.852	92.092	86.440	19.421	18.566
337	DCIP	22	22.785	21.852	92.088	86.436	19.421	18.566
338	DCIP	22	22.785	21.852	92.084	86.432	19.421	18.566
339	DCIP	19	25.458	23.662	108.918	97.503	21.878	20.226
340	DCIP	22	22.785	21.852	92.075	86.424	19.421	18.566
341	DCIP	22	22.785	21.852	92.071	86.420	19.421	18.566
342	DCIP	22	22.785	21.852	92.067	86.416	19.421	18.566
343	DCIP	19	25.458	23.662	108.898	97.485	21.878	20.226
344	DCIP	19	25.458	23.662	108.893	97.480	21.877	20.226
345	DCIP	19	25.458	23.662	108.888	97.476	21.877	20.226
346	DCIP	19	25.458	23.662	108.883	97.471	21.877	20.225
347	DCIP	19	25.458	23.662	108.878	97.467	21.877	20.225
348	DCIP	19	25.458	23.662	108.873	97.462	21.877	20.225
349	DCIP	19	25.458	23.662	108.868	97.458	21.877	20.225
350	DCIP	19	25.458	23.662	108.863	97.453	21.877	20.225

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351	DCIP	19	25.458	23.662	98.253	87.955	21.549	19.913
352	DCIP	19	25.458	23.662	108.853	97.444	21.876	20.225
353	DCIP	19	25.458	23.662	108.848	97.440	21.876	20.225
354	DCIP	19	25.458	23.662	108.843	97.435	21.876	20.224
355	DCIP	19	25.458	23.662	108.838	97.431	21.876	20.224
356	DCIP	19	25.458	23.662	108.833	97.426	21.876	20.224
357	DCIP	19	25.458	23.662	108.828	97.422	21.876	20.224
358	DCIP	19	25.458	23.662	108.823	97.417	21.875	20.224
359	DCIP	19	18.233	16.996	52.516	47.214	14.668	13.575
360	DCIP	19	25.458	23.662	108.813	97.409	21.875	20.224
361	DCIP	19	25.458	23.662	108.808	97.404	21.875	20.223
362	DCIP	19	25.458	23.662	108.803	97.400	21.875	20.223
363	DCIP	19	25.458	23.662	108.798	97.395	21.875	20.223
364	DCIP	19	25.458	23.662	108.793	97.391	21.875	20.223
365	DCIP	19	25.458	23.662	108.788	97.386	21.874	20.223
366	DCIP	19	25.458	23.662	108.783	97.382	21.874	20.223
367	DCIP	19	25.458	23.662	108.778	97.377	21.874	20.223
368	DCIP	19	25.458	23.662	108.773	97.373	21.874	20.222
369	DCIP	19	18.233	16.996	52.492	47.192	14.667	13.574
370	DCIP	19	25.458	23.662	108.763	97.364	21.874	20.222
371	DCIP	19	25.458	23.662	108.758	97.359	21.874	20.222
372	DCIP	19	25.458	23.662	108.753	97.355	21.873	20.222
373	DCIP	19	25.458	23.662	108.748	97.350	21.873	20.222
374	DCIP	19	25.458	23.662	108.743	97.346	21.873	20.222
375	DCIP	19	25.458	23.662	108.738	97.341	21.873	20.222
376	DCIP	19	25.458	23.662	108.733	97.337	21.873	20.221
377	DCIP	19	25.458	23.662	108.728	97.333	21.873	20.221
378	DCIP	19	25.458	23.662	108.723	97.328	21.873	20.221
379	DCIP	19	25.458	23.662	108.718	97.324	21.872	20.221
380	DCIP	19	11.857	11.179	19.106	17.477	8.266	7.721
381	DCIP	19	25.458	23.662	108.708	97.315	21.872	20.221
382	DCIP	19	25.458	23.662	108.703	97.310	21.872	20.221
383	DCIP	19	25.458	23.662	108.698	97.306	21.872	20.220
384	DCIP	19	25.458	23.662	108.693	97.301	21.872	20.220
385	DCIP	19	25.458	23.662	108.688	97.297	21.872	20.220
386	DCIP	19	9.845	9.462	11.042	10.399	6.062	5.780
387	DCIP	19	9.845	9.462	11.042	10.399	6.062	5.780
388	DCIP	19	9.845	9.462	11.041	10.399	6.062	5.780

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389	DCIP	19	25.458	23.662	98.062	87.784	21.543	19.906
390	DCIP	22	22.785	21.852	91.864	86.226	19.414	18.560
391	DCIP	19	25.458	23.662	108.659	97.270	21.871	20.219
392	DCIP	22	22.785	21.852	91.856	86.218	19.414	18.559
393	DCIP	19	25.458	23.662	108.649	97.261	21.871	20.219
394	DCIP	19	25.458	23.662	108.644	97.257	21.870	20.219
395	DCIP	23	10.083	9.859	14.011	13.542	6.705	6.531
396	DCIP	19	25.458	23.662	108.634	97.248	21.870	20.219
397	DCIP	19	25.458	23.662	108.629	97.243	21.870	20.219
398	DCIP	19	25.458	23.662	108.624	97.239	21.870	20.218
399	DCIP	19	25.458	23.662	108.619	97.234	21.870	20.218
400	DCIP	22	22.785	21.852	91.822	86.187	19.413	18.558
401	DCIP	22	16.390	15.745	44.604	41.974	13.037	12.471
402	DCIP	19	25.458	23.662	108.604	97.221	21.869	20.218
403	DCIP	22	22.785	21.852	91.810	86.175	19.413	18.558
404	DCIP	22	22.785	21.852	91.805	86.171	19.412	18.558
405	DCIP	22	22.785	21.852	91.801	86.167	19.412	18.558
406	DCIP	22	22.785	21.852	91.797	86.163	19.412	18.557
407	DCIP	22	22.785	21.852	91.793	86.159	19.412	18.557
408	DCIP	22	22.785	21.852	91.789	86.155	19.412	18.557
409	DCIP	22	22.785	21.852	91.784	86.151	19.412	18.557
410	DCIP	22	22.785	21.852	91.780	86.147	19.412	18.557
411	DCIP	22	22.785	21.852	91.776	86.143	19.412	18.557
412	DCIP	19	11.857	11.179	17.244	15.773	8.004	7.472
413	DCIP	19	18.233	16.996	52.387	47.098	14.661	13.568
414	DCIP	19	25.458	23.662	108.544	97.168	21.868	20.216
415	DCIP	22	22.785	21.852	91.759	86.127	19.411	18.556
416	DCIP	22	22.785	21.852	91.755	86.124	19.411	18.556
417	DCIP	19	25.458	23.662	97.922	87.658	21.538	19.902
418	DCIP	19	25.458	23.662	97.917	87.654	21.538	19.902
419	DCIP	19	25.458	23.662	108.519	97.145	21.867	20.216
420	DCIP	19	25.458	23.662	108.514	97.141	21.867	20.215
421	DCIP	19	25.458	23.662	108.509	97.136	21.867	20.215
422	DCIP	19	25.458	23.662	108.504	97.132	21.866	20.215
423	DCIP	19	25.458	23.662	108.499	97.127	21.866	20.215
424	DCIP	19	25.458	23.662	108.494	97.123	21.866	20.215
425	DCIP	19	25.458	23.662	108.489	97.119	21.866	20.215
426	DCIP	22	22.785	21.852	91.713	86.084	19.410	18.555

3. Continued

427	DCIP	22	22.785	21.852	91.709	86.080	19.409	18.555
428	DCIP	14	16.835	15.021	38.118	32.080	12.859	11.313
429	DCIP	21	10.291	9.926	13.854	13.118	6.771	6.489
430	DCIP	21	10.291	9.926	12.700	12.025	6.566	6.291
431	DCIP	13	12.518	11.416	18.721	16.285	8.527	7.658
432	DCIP	13	12.518	11.416	18.720	16.285	8.527	7.658
433	DCIP	13	12.518	11.416	18.165	15.802	8.444	7.582
434	DCIP	13	12.518	11.416	18.164	15.802	8.444	7.582
435	DCIP	14	16.835	15.021	38.105	32.069	12.858	11.312
436	DCIP	14	16.835	15.021	38.103	32.067	12.858	11.312
437	DCIP	14	16.835	15.021	38.101	32.065	12.858	11.312
438	DCIP	14	16.835	15.021	38.099	32.064	12.858	11.312
439	DCIP	14	16.835	15.021	38.097	32.062	12.858	11.312
440	DCIP	14	16.835	15.021	38.095	32.061	12.858	11.312
441	DCIP	14	16.835	15.021	38.093	32.059	12.857	11.311
442	DCIP	14	16.835	15.021	38.091	32.057	12.857	11.311
443	DCIP	14	30.241	26.811	136.779	114.005	26.188	23.022
444	DCIP	14	21.524	19.166	65.441	54.904	17.496	15.402
445	DCIP	14	21.524	19.166	65.438	54.901	17.496	15.402
446	DCIP	14	21.524	19.166	65.434	54.898	17.496	15.402
447	DCIP	14	21.524	19.166	65.431	54.895	17.495	15.402
448	DCIP	14	21.524	19.166	65.428	54.893	17.495	15.402
449	DCIP	14	21.524	19.166	65.424	54.890	17.495	15.401
450	DCIP	14	21.524	19.166	65.421	54.887	17.495	15.401
451	DCIP	14	21.524	19.166	65.418	54.884	17.495	15.401
452	DCIP	14	30.241	26.811	136.716	113.952	26.186	23.020
453	DCIP	14	30.241	26.811	136.709	113.946	26.186	23.020
454	DCIP	23	9.768	9.567	12.855	12.455	6.377	6.222
455	DCIP	19	9.845	9.462	9.991	9.409	5.826	5.553
456	DCIP	19	9.845	9.462	10.087	9.500	5.849	5.575
457	DCIP	19	9.845	9.462	10.108	9.520	5.854	5.580
458	DCIP	19	9.845	9.462	10.108	9.519	5.854	5.580
459	DCIP	22	9.273	9.069	9.307	9.000	5.463	5.318
460	DCIP	22	9.273	9.069	6.227	6.022	4.540	4.415
461	DCIP	6	10.396	9.632	8.904	7.934	5.721	5.207
462	DCIP	22	9.273	9.069	9.124	8.823	5.418	5.274
463	DCIP	13	12.518	11.416	18.700	16.268	8.524	7.655
464	DIP	25	0.017	0.017	0.001	0.001	0.001	0.001

3. Continued

465	DIP	25	0.017	0.017	0.001	0.001	0.001	0.001
466	DIP	26	1.207	1.156	0.449	0.420	0.419	0.395
467	DIP	26	1.207	1.156	0.449	0.420	0.419	0.395
468	DIP	26	0.201	0.171	0.033	0.026	0.038	0.030
469	DIP	26	1.694	1.641	0.708	0.675	0.633	0.607
470	DIP	26	1.694	1.641	0.708	0.675	0.633	0.607
471	DIP	26	1.694	1.641	0.708	0.675	0.633	0.607
472	DIP	25	0.009	0.013	0.000	0.000	0.000	0.001
473	DIP	25	0.009	0.013	0.000	0.000	0.000	0.001
474	DIP	26	1.207	1.156	0.495	0.463	0.446	0.421
475	DIP	26	1.694	1.641	0.708	0.675	0.633	0.607
476	DIP	26	0.688	0.643	0.205	0.185	0.205	0.187
477	DIP	26	1.694	1.641	0.708	0.675	0.633	0.607
478	DIP	32	0.029	0.028	0.002	0.002	0.000	0.000
479	DIP	32	1.112	1.615	0.365	0.646	0.355	0.587
480	DIP	32	1.112	1.615	0.400	0.709	0.378	0.623
481	DIP	32	1.112	1.615	0.396	0.701	0.375	0.618
482	DIP	35	0.617	1.255	0.161	0.482	0.168	0.445
483	DIP	35	0.617	1.255	0.161	0.482	0.168	0.445
484	DIP	32	1.112	1.615	0.402	0.713	0.379	0.625
485	DIP	32	1.112	1.615	0.400	0.709	0.378	0.623
486	DIP	32	1.112	1.615	0.396	0.701	0.375	0.618
487	DIP	32	1.112	1.615	0.396	0.701	0.375	0.618
488	DIP	35	0.202	0.649	0.023	0.142	0.028	0.155
489	DIP	32	1.112	1.615	0.400	0.709	0.378	0.622
490	DIP	32	1.112	1.615	0.355	0.629	0.348	0.577
491	DIP	35	0.238	0.764	0.039	0.240	0.045	0.237
492	DIP	32	1.112	1.615	0.400	0.709	0.378	0.623
493	DIP	32	1.112	1.615	0.400	0.709	0.378	0.622
494	DIP	32	0.029	0.028	0.002	0.002	0.000	0.000
495	DIP	32	0.541	0.930	0.124	0.287	0.134	0.285
496	DIP	25	0.365	0.252	0.094	0.052	0.098	0.058
497	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
498	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
499	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
500	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
501	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
502	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002

3. Continued

503	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
504	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
505	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
506	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
507	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
508	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
509	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
510	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
511	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
512	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
513	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
514	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
515	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
516	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
517	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
518	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
519	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
520	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
521	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
522	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
523	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
524	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
525	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
526	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
527	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
528	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
529	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
530	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
531	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
532	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
533	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
534	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
535	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
536	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
537	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
538	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
539	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
540	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002

3. Continued

541	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
542	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
543	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
544	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
545	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
546	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
547	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
548	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
549	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
550	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
551	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
552	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
553	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
554	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
555	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
556	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
557	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
558	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
559	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
560	DIP	25	0.384	0.223	0.150	0.062	0.137	0.064
561	DIP	25	0.384	0.223	0.150	0.062	0.137	0.064
562	DIP	25	0.365	0.228	0.118	0.056	0.115	0.059
563	DIP	25	0.365	0.228	0.118	0.056	0.115	0.059
564	DIP	25	0.365	0.228	0.118	0.056	0.115	0.059
565	DIP	25	0.365	0.228	0.118	0.056	0.115	0.059
566	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
567	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
568	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
569	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
570	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
571	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
572	DIP	24	0.011	0.025	0.000	0.002	0.000	0.002
573	DIP	24	0.709	0.359	0.394	0.134	0.314	0.125
574	DIP	24	0.709	0.359	0.394	0.134	0.314	0.125
575	DIP	24	0.709	0.359	0.394	0.134	0.314	0.125
576	DIP	24	0.709	0.359	0.394	0.134	0.314	0.125
577	DIP	24	0.709	0.359	0.394	0.134	0.314	0.125
578	DIP	24	0.709	0.359	0.394	0.134	0.314	0.125

3. Continued

579	DIP	24	0.709	0.359	0.394	0.134	0.314	0.125
580	DIP	24	0.709	0.359	0.394	0.134	0.314	0.125
581	DIP	24	0.723	0.296	0.502	0.120	0.360	0.108
582	DIP	26	0.727	0.674	0.264	0.235	0.248	0.224
583	DIP	24	0.723	0.296	0.454	0.108	0.342	0.101
584	DIP	24	0.709	0.359	0.356	0.121	0.296	0.117
585	DIP	24	0.709	0.359	0.356	0.121	0.296	0.117
586	DIP	24	0.709	0.359	0.356	0.121	0.296	0.116
587	DIP	24	0.709	0.359	0.394	0.134	0.314	0.125
588	DIP	24	0.709	0.359	0.394	0.134	0.314	0.125
589	DIP	25	0.999	0.816	0.431	0.315	0.381	0.290
590	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
591	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
592	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
593	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
594	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
595	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
596	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
597	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
598	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
599	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
600	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
601	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
602	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
603	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
604	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
605	DIP	25	0.025	0.025	0.002	0.002	0.002	0.002
606	DIP	24	0.709	0.359	0.394	0.133	0.314	0.124
607	DIP	35	0.617	1.255	0.158	0.474	0.166	0.440
608	DIP	32	0.007	0.007	0.000	0.000	0.000	0.000
609	DIP	35	0.008	0.008	0.000	0.000	0.000	0.000
610	DIP	35	0.002	0.297	0.000	0.058	0.000	0.065
611	DIP	28	0.779	0.911	0.224	0.285	0.227	0.282
612	DIP	32	0.007	0.007	0.000	0.000	0.000	0.000
613	DIP	32	0.007	0.007	0.000	0.000	0.000	0.000
614	DIP	35	0.002	0.297	0.000	0.058	0.000	0.065
615	DIP	35	0.002	0.297	0.000	0.059	0.000	0.066
616	DIP	35	0.002	0.297	0.000	0.059	0.000	0.066

3. Continued

617	DIP	35	0.002	0.297	0.000	0.059	0.000	0.066
618	DIP	35	0.002	0.297	0.000	0.059	0.000	0.065
619	DIP	35	0.002	0.297	0.000	0.059	0.000	0.066
620	DIP	35	0.002	0.297	0.000	0.059	0.000	0.066
621	DIP	35	0.002	0.297	0.000	0.059	0.000	0.066
622	DIP	35	0.002	0.297	0.000	0.057	0.000	0.064
623	DIP	35	0.002	0.297	0.000	0.059	0.000	0.066
624	DIP	35	0.015	0.014	0.000	0.000	0.000	0.000
625	DIP	35	0.015	0.014	0.000	0.000	0.000	0.000
626	DIP	35	0.015	0.014	0.000	0.000	0.000	0.000
627	DIP	35	0.238	0.764	0.039	0.239	0.045	0.236
628	DIP	35	0.238	0.764	0.039	0.239	0.045	0.236
629	DIP	35	0.238	0.764	0.039	0.240	0.045	0.236
630	DIP	35	0.002	0.297	0.000	0.059	0.000	0.066
631	DIP	35	0.002	0.297	0.000	0.058	0.000	0.065
632	DIP	28	0.881	1.037	0.300	0.386	0.288	0.360
633	DIP	28	0.881	1.037	0.304	0.391	0.291	0.363
634	DIP	35	0.002	0.297	0.000	0.055	0.000	0.062
635	DIP	28	0.331	0.435	0.065	0.100	0.073	0.108
636	DIP	28	0.331	0.435	0.065	0.100	0.073	0.108
637	DIP	28	0.881	1.037	0.300	0.386	0.288	0.360
638	DIP	28	0.881	1.037	0.300	0.386	0.288	0.360
639	DIP	28	0.881	1.037	0.300	0.386	0.288	0.360
640	DIP	28	1.992	2.163	0.889	1.007	0.775	0.864
641	DIP	28	1.992	2.163	0.867	0.983	0.764	0.851
642	DIP	28	1.992	2.163	0.860	0.974	0.760	0.847
643	DIP	28	1.992	2.163	0.867	0.983	0.764	0.851
644	DIP	28	1.992	2.163	0.819	0.928	0.737	0.822
645	DIP	28	1.992	2.163	0.819	0.928	0.737	0.822
646	DIP	28	1.460	1.628	0.603	0.712	0.542	0.626
647	DIP	28	1.460	1.628	0.525	0.621	0.496	0.574
648	DIP	35	0.617	1.255	0.158	0.471	0.165	0.438
649	DIP	35	0.617	1.255	0.154	0.459	0.162	0.431
650	DIP	35	0.617	1.255	0.160	0.479	0.167	0.443
651	DIP	35	0.617	1.255	0.161	0.482	0.168	0.445
652	DIP	35	0.617	1.255	0.154	0.459	0.162	0.431
653	DIP	35	0.617	1.255	0.154	0.459	0.162	0.431
654	DIP	32	1.573	2.092	0.584	0.903	0.545	0.798

3. Continued

655	DIP	32	1.573	2.092	0.584	0.903	0.545	0.798
656	DIP	32	1.573	2.092	0.604	0.933	0.557	0.814
657	DIP	32	1.573	2.092	0.624	0.964	0.569	0.831
658	DIP	37	1.496	2.322	0.562	1.098	0.522	0.936
659	DIP	37	1.496	2.322	0.532	1.039	0.504	0.906
660	DIP	37	1.496	2.322	0.509	0.995	0.489	0.882
661	DIP	37	1.496	2.322	0.509	0.995	0.489	0.882
662	DIP	37	1.496	2.322	0.543	1.062	0.511	0.918
663	DIP	37	1.496	2.322	0.543	1.062	0.511	0.918
664	DIP	35	1.032	1.724	0.337	0.739	0.328	0.655
665	DIP	35	1.032	1.724	0.337	0.739	0.328	0.655
666	DIP	35	1.032	1.724	0.337	0.739	0.328	0.655
667	DIP	35	1.032	1.724	0.337	0.739	0.328	0.655
668	DIP	35	1.032	1.724	0.339	0.744	0.330	0.657
669	DIP	35	1.032	1.724	0.339	0.744	0.330	0.657
670	DIP	35	1.032	1.724	0.339	0.744	0.330	0.657
671	DIP	37	1.496	2.322	0.605	1.183	0.548	0.978
672	DIP	35	1.032	1.724	0.339	0.744	0.330	0.657
673	DIP	37	1.496	2.322	0.606	1.185	0.549	0.979
674	DIP	35	0.008	0.008	0.000	0.000	0.000	0.000
675	DIP	35	0.617	1.255	0.158	0.472	0.165	0.439
676	DIP	35	0.617	1.255	0.158	0.472	0.165	0.439
677	DIP	35	0.617	1.255	0.161	0.481	0.168	0.444
678	DIP	35	0.617	1.255	0.161	0.481	0.167	0.444
679	DIP	35	0.617	1.255	0.161	0.481	0.167	0.444
680	DIP	35	0.617	1.255	0.158	0.472	0.165	0.439
681	DIP	35	0.617	1.255	0.154	0.462	0.162	0.432
682	DIP	35	0.617	1.255	0.154	0.462	0.162	0.432
683	DIP	35	0.617	1.255	0.161	0.480	0.167	0.444
684	DIP	35	0.617	1.255	0.160	0.478	0.167	0.442
685	DIP	35	0.617	1.255	0.160	0.478	0.167	0.442
686	DIP	35	0.617	1.255	0.160	0.478	0.167	0.442
687	DIP	35	0.617	1.255	0.161	0.480	0.167	0.444
688	DIP	35	0.617	1.255	0.160	0.478	0.167	0.442
689	DIP	35	0.202	0.649	0.026	0.163	0.032	0.171
690	DIP	35	0.617	1.255	0.160	0.479	0.167	0.443
691	DIP	35	0.617	1.255	0.160	0.479	0.167	0.443
692	DIP	32	1.573	2.092	0.604	0.932	0.557	0.814

3. Continued

693	DIP	32	1.573	2.092	0.604	0.932	0.557	0.814
694	DIP	32	1.573	2.092	0.630	0.973	0.573	0.835
695	DIP	32	1.573	2.092	0.630	0.973	0.573	0.835
696	DIP	35	0.617	1.255	0.149	0.446	0.158	0.422
697	DIP	35	0.617	1.255	0.154	0.461	0.162	0.432
698	DIP	35	0.202	0.649	0.029	0.177	0.034	0.182
699	DIP	35	0.617	1.255	0.160	0.478	0.167	0.442
700	DIP	28	1.239	1.382	0.433	0.512	0.413	0.478
701	DIP	28	1.239	1.382	0.433	0.512	0.413	0.478
702	DIP	28	0.230	0.303	0.028	0.043	0.034	0.051
703	DIP	37	1.496	2.322	0.538	1.051	0.508	0.912
704	DIP	35	0.293	0.938	0.068	0.416	0.073	0.364
705	DIP	28	0.881	1.037	0.299	0.385	0.288	0.359
706	DIP	35	0.002	0.297	0.000	0.059	0.000	0.066
707	DIP	32	1.573	2.092	0.617	0.954	0.565	0.825
708	DIP	35	0.617	1.255	0.161	0.481	0.167	0.444
709	DIP	28	1.460	1.628	0.640	0.757	0.562	0.650
710	DIP	35	0.617	1.255	0.158	0.471	0.165	0.438
711	DIP	35	0.617	1.255	0.160	0.479	0.167	0.443
712	DIP	28	1.992	2.163	0.818	0.927	0.737	0.821
713	SP	35	2.242	2.242	1.871	1.871		
714	SP	7	6.063	6.063	4.099	4.099		
715	SP	21	4.468	4.468	3.174	3.174		
716	SP	22	3.848	3.848	2.049	2.049		
717	SP	21	4.468	4.468	3.479	3.479		
718	SP	34	3.201	3.201	2.067	2.067		

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